Ling-Chin J, Roskilly AP.

Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective – A life cycle assessment case study.

Applied Energy 2016, 181, 416–434

DOI link to article:

http://dx.doi.org/10.1016/j.apenergy.2016.08.065

Date deposited:

19/10/2016

Applied Energy 181 (2016) 416–434

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective – A life cycle assessment case study

Janie Ling-Chin *, Anthony P. Roskilly

Sir Joseph Swan Centre for Energy Research, Newcastle University, NE1 7RU, UK

HIGHLIGHTS

- Resources, emissions and impact from manufacture to end of life were estimated.
- Operating diesel gensets and disposing metallic scrap were significant processes.
- Correlations between fuel consumption and impact categories were identified.
- The influence of the end of life scenarios on ecotoxicity potential was studied.
- Environmental benefits of the hybrid system were compared and verified.

ARTICLE INFO

Article history:
Received 3 April 2016
Received in revised form 10 August 2016
Accepted 12 August 2016

Keywords:
Life cycle assessment (LCA)
Environmental impact
Resource consumption
Marine electric power system
Integrated system approach
Hybrid power system

ABSTRACT

Marine transport has been essential for international trade. Concern for its environmental impact was growing among regulators, classification societies, ship operators, ship owners, and other stakeholders. By applying life cycle assessment, this article aimed to assess the impact of a new-build hybrid system (i.e. an electric power system which incorporated lithium ion batteries, photovoltaic systems and cold-ironing) designed for Roll-on/Roll-off cargo ships. The study was carried out based on a bottom-up integrated system approach using the optimised operational profile and background information for manufacturing processes, mass breakdown and end of life management plans. Resources such as metallic and non-metallic materials and energy required for manufacture, operation, maintenance, dismantling and scrap handling were estimated. During operation, 1.76×10^8 kg of marine diesel oil was burned, releasing carbon monoxide, carbon dioxide, particulate matter, hydrocarbons, nitrogen oxides and sulphur dioxide which ranged 5–8 orders of magnitude. The operation of diesel gensets was the primary cause of impact categories that were relevant to particulate matter or respiratory inorganic health issues, photochemical ozone creation, eutrophication, acidification, global warming and human toxicity. Disposing metallic scrap was accountable for the most significant impact category, ecotoxicity potential. The environmental benefits of the hybrid power system in most impact categories were verified in comparison with a conventional power system onboard cargo ships. The estimated results for individual impact categories were verified using scenario analysis. The study concluded that the life cycle of a new-build hybrid power system would result in significant impact on the environment, human beings and natural reserves, and therefore proper management of such a system was imperative.

1. Introduction

Among all transport modes, marine transport has been predominant. It enabled more than 80% of merchandise trade globally [1]. The business, by its very nature, was complex. It affected and was affected by

- legislation e.g. Marine Pollution (MARPOL) Annex VI *Regulations for the Prevention of Air Pollution from Ships* and Energy Efficiency Design Index (EEDI) which were enforced by International Maritime Organisation (IMO),
- economics e.g. capital investment of technologies and fuel cost,
- technologies e.g. choice, system designs and vessel types, and
- operation e.g. efficiency, sailing routes and speeds.

* Corresponding author.
E-mail address: j.l.chin@ncl.ac.uk (J. Ling-Chin).

http://dx.doi.org/10.1016/j.apenergy.2016.08.065
0306-2619/

The business involved a wide range of stakeholders including but not limited to ship owners, operators, builders, classification societies, authorities, regulators and researchers. In all circumstances, energy efficiency and technologies were at the core of research and development. The scientific findings were crucial as they could offer insightful information to the stakeholders and assist their decision making.

A number of research areas have already been explored. For instance, the influence of EEDI on future propulsion system designs for liquefied natural gas carriers was investigated by [2]. Based on the operational data, energy efficiency of feeders was evaluated by [3] which took sailing speeds, cargo capacity and time spent in port and at sea into account. Using a life-cycle energy management tool, energy efficiency of container ships was estimated by [4] which considered configuration designs and operational profiles. Based on the real-time operational profiles of two relevant ships, the potential of improving energy efficiency via shorter waiting time in port was explored by [5]. An artificial neural network (ANN) was applied by [6] in developing a model for fuel consumption prediction to support decision making for energy efficient operation. A framework was developed by [7] to assist ship owners in breaking down barriers to energy efficiency enhancement. Fuel consumption required for crane operation which involved the use of a battery, a diesel generator and a control system was estimated by [8].

In relation to prime mover technologies, diesel engines have been broadly researched to cover different aspects. Combustion models were developed for 2- or 4-stroke engines to analyse soot formation [9], nitrogen oxides (NO_X) formation and the use of exhaust gas recirculation (EGR) [10], effect of variation in engine loads [11], pilot injection for efficiency improvement and NOx reduction [12], scavenging flow and temperature distribution in the piston crown [13] as well as characterisation of particulate matter (PM) at various engine settings [14]. In addition, models were also developed to evaluate engine performance at slow steaming conditions [15], various sailing scenarios [16] and based on a zero-dimensional approach [17]. The concept of a multidimensional model which could be used as an engine diagnostic tool was proposed by [18].

A search for optimisation and advancement in technologies have been stimulated. This included waste heat recovery (WHR), fuel cells, wind propulsion and cold-ironing, to name a few. For example, operational (in terms of business route, ship trim, hull, propeller and engine performance), technical (including propeller programming, fuel slide valves, oil consumption and retrofit) and commercial (such as slow steaming, speed and fuel consumption) optimisation tools were reviewed by [19]. Based on a holistic approach, advanced computer-aided techniques were investigated by [20] for ship design optimisation. Sailing speed optimisation for ships that transited across Emission Control Areas (ECAs) was investigated by [21]. Focussing on WHR, the optimised thermodynamic and economic performance of an organic Rankine cycle (ORC) system was investigated by [22]. Covering fundamental principles, technical designs and economic aspects, WHR technologies were reviewed by [23]. Cooling systems powered by waste heat absorption and vapour compression cycles respectively were modelled and compared by [24]. Two propulsion options for ferries and Roll-on/Roll-off (RoRo) cargo ships, i.e. a dual fuel engine employing a WHR system and a conventional diesel engine were compared by [25] from technical and economic perspectives. Focussing on a diesel engine which integrated a WHR system, different optimisation possibilities that considered various control variables were studied by [26]. Marine power system designs which employed various types of fuel cells were presented by [27]. A marine trigeneration system which incorporated diesel generators, a solid oxide fuel cell, a gas turbine and an absorption heat pump was proposed by [28]. In addition, the optimal sizing method for a marine power system that integrated diesel engines, PV and battery systems under different operating conditions was proposed by [29]. Wind propulsion technologies including Flettner rotors and towing kites were modelled by [30] in addition to a hard sail study reported by [31]. For cold-ironing technologies, the shore-side design and control aspects were investigated by [32], electrical characteristics of the installation were examined by [33] and social-economic benefits were addressed by [34]. All these studies shared a common vision i.e. innovative technologies and techniques could address technical challenges and offer solutions to mitigate the environmental impact caused by maritime business, which in turn could protect the environment, society and natural reserves from further damage, as implied in [35].

Legislation, research and innovative development relevant to maritime business have been driven by increasing global concern over the environmental sustainability of marine transport. Marine transport was perceived to be more environmentally friendly than other modes *per unit of cargo shipped and distance travelled*. Still, its contribution to global emissions has been continual. Marine transport contributed, for instance, 2.1–2.2% of global carbon dioxide (CO_2) and CO_2-equivalent greenhouse gas (GHG) emissions in 2012, which accounted for 938 and 961 megatonnes respectively [36]. Some studies on marine transport primarily focused on emissions (in particular GHGs which were the major cause of climate change) without elucidating environmental issues, as implied by [37]. Relevant examples included [38–40]. The relationship between CO_2 emission and other factors such as ship types, sizes and the geographic setting was explored by [38]. To what extent efficient shipping could help reduce global CO_2 emissions was analysed by [39]. Emissions, cost and profit for the design of bulk vessels was investigated by [40]. A plausible explanation was that CO_2 emission had been adopted as a means to measure energy efficiency of marine power systems as in EEDI [2] whilst other GHG emissions were of lower magnitude and contributed less towards climate change. However, estimating GHG emissions and climate change was not enough as it did not present a full picture of the impact of marine transport on the natural environment. Climate change only represented one of the attributes of natural environment from a life cycle assessment (LCA) perspective, which was a common tool applied for environmental assessment. Any unnatural change in the attributes of human health and/or natural resources was indeed within the scope of environmental issues, which would affect the society directly and indirectly. Examples of environmental issues included

(i) ecotoxicity (for freshwater and marine aquatic, sediment and terrestrial ecosystems), acidification, eutrophication and photochemical oxidant formation in respect of natural environment;
(ii) noise, odour, ionising radiation, casualties, thermal pollution and human toxicity (such as respiratory, cancer and non-cancer effects) in relation to human health; and
(iii) freshwater consumption, depletion of fossil fuels and mineral resources relevant to natural resources.

Some impact categories were applicable to the marine context, as summarised in the supplementary material (Appendix 1) together with a brief description of the impact categories. In addressing the environmental issues, LCA has been practised in the marine context up to now, which covered software development, vessels, power technologies and systems, emission abatement techniques, fuels and waste, as summarised in Table 1. A scale of I–IV was adopted to describe how far the environmental impact of shipping or relevant technology has been assessed (from I which was for no coverage to IV which was for estimating more

Table 1
Focus, coverage of environmental impact, objective and limitation of existing LCA literature relevant to marine transport.

Focus, coverage[a]	Literature type[b]	Objective	Limitation
Shipping software, II	II [41]	To develop a tool that can be used in ship design for estimating life cycle burdens	Brief and limited to the selected components and data; neither LCIA results nor the computer tool itself was available
Shipping software, I	III [42]	To create an LCI database and outline the development of LCA software for ships	The software and operational data e.g. fuel type and consumption were not available; emissions were reported as environmental impact
Shipping software, III	I [43]	To establish methodology and develop LCA software for ships	Manufacturing was not included in the scope
Shipping software, II	I [44]	To offer a tool developed in SimaPro to assess environmental impact during ship design phase	The software tool was not available; impractical as the environmental impact or emission reduction of a technology is required to calculate the index
Shipping software, II	I [45]	To develop a demonstrator for an eco-design tool integrating with environmental assessment	Neither the demonstrator nor the tool was available; only very limited LCI data and LCIA results were presented
Shipping software, II	I [46]	To develop a tool which models environmental, cost and safety aspects of marine technologies	The tool was not available; data and details of environmental, economic and social assessments were mostly not reported
Shipping, II	II [47]	To establish research basis of impact assessment for ships, including system boundaries	The study was only a screening analysis in which cut-off and scrapping were excluded
Shipping, IV	I [48]	To present requirements for environmental reporting	Transport chains of cargo vessels, ferries and trucks were studied but not fully reported
Shipping, IV	II [49]	To compare the impacts of 2 ferries made of steel and carbon fibre reinforced composite	Data regarding emissions, engines and fuel combustion were from literature or Ecoinvent instead of primary data source
Auxiliary power, IV	I [50]	To compare the environmental impact of a low sulphur fuelled molten carbonate fuel cell (MCFC) and diesel engine (DE)	No information about the reference ship; only 1 DE was assessed although 3 units were installed; reformer required for the MCFC system was not considered
Auxiliary power, IV	I [51]	To compare the environmental impact of a methanol fuelled solid oxide fuel cell (SOFC) and a conventional DE	The lifespans of SOFC and DE were not considered; the comparison was made for 1kWh electricity generated without reporting total impact
Power technology, IV	IV [52]	To compare fuel cell, gas and diesel engines in terms of environmental impacts	The functional unit was not appropriately defined. It was not clear if the system was for main or auxiliary power
Power technology, II	I [53]	To analysis LCA methodology development and develop an LCA framework for marine PV systems	Limited to literature review and framework development without practical applications
Power system, IV	I [54]	To investigate the environmental benefits of a power system	Limited to a conventional and retrofit design onboard a RoRo cargo ship
Emission abatement, III	I [55]	To examine the options of SOx abatement applicable onboard ocean-going ships	Only energy use and GHG emissions were assessed per nautical mile of distance travelled
Marine fuels, III	I [56]	To assess the environmental performance of 4 fuel types with/without emission abatement	No account for reference ship, as did real-time data and total fuel consumption by the engine
Marine fuels, IV	I [57]	To evaluate the life cycle performance of 4 types of biofuels for shipping application	Selective catalytic reduction, infrastructure, real-time operation and fuel consumption differentiation was not considered
Marine waste, IV	I [58]	To assess onshore units for treating ship-generated waste, i.e. bilge water, solid waste etc.	Most data were not country specific and data for cement production plant were limited; all processes with a contribution less than 0.35% were excluded
Framework, I	I [59]	To propose a framework for air emissions which was supported by a case study	Limited to hull and machinery system, diesel oil and steel were the only resources under assessment, and no environmental impact was assessed

[a] Coverage of environmental impact: I No coverage; II Recognition without any estimate; III Assessment of 1–3 impact categories; and IV Assessment of more than 3 impact categories.
[b] Literature type: I Journal article; II Report; III Conference proceeding/paper; and IV Thesis.

than 3 impact categories). Compared to the wide range of vessel types, technologies, design configurations and operational profiles, the number of such studies was relatively limited. More LCA case studies broadening the current scope were therefore imperative in line with the direction towards sustainable shipping.

The environmental impact of marine transport has been in proximity with technologies that could address shipping emissions and energy efficiency. Promoting and implementing such technologies to mitigate the environmental impact of marine transport was regarded as an important issue, as indicated by large-scale on-going international projects:

(i) a €10 million grant which was funded by the European Commission to IMO to establish Maritime Technology Cooperation Centres in Asia, Africa, the Caribbean, the Pacific and Latin America to promote technologies for emission abatement and energy efficiency improvement [60];
(ii) an up to US$ 2 million of US Federal funding which was allocated by the Maritime Administration (MARAD) for the Low Emission Accelerator Partnership (LEAP) project to advance low-emission development for marine transport [61]; and
(iii) an US$ 2 million grant which was put together by IMO, the United Nations Development Programme (UNDP) and the Global Environment Facility (GEF) to run the Global Maritime Energy Efficiency Partnership Project [62].

In general, merchant ships comprised general cargo, container, RoRo cargo, passenger ships, oil/chemical tankers, bulk/gas carriers and support vessels. From an economic perspective, the conventional power systems (i.e. diesel mechanical systems) have remained advantageous for vessels such as tankers, carriers and container ships which would operate at low speeds and applied slow steaming. If additional cargo capacity was desired by these cargo ships, electric systems would be beneficial. For RoRo cargo and passenger ships which required improved manoeuvrability and involved high electric power demand, electric systems would be suitable [63]. Indeed, electric systems have been researched and applied in cruise ships, as noted by [64,65]. Literature examples included

- [63] which discussed design and control concepts, components, systems and future trends;

- [66] which presented terminology and dependability theory of integrated power system fundamentally required for electric propulsion;
- [67] which focused on challenges and novel trends of electric power generation schemes;
- [68] which proposed a control system for economic and environmental operation;
- [69] which discussed the benefits and challenges of marine electric systems and how they were affected by recent development in power conversion technologies; and
- [70] which overviewed the past, present and future of electric ships.

Particularly for RoRo cargo and other ship types, neither have electric power systems been commercially applied nor assessed from an LCA perspective. The number of global vessels was dynamic due to the demolition of old ships and the construction of new-build ships year after year. For instance, 22.4 million of gross tonnage were sold for demolition and more than 309.4 million of deadweight tonnage were ordered in 2014 [1]. Therefore, the opportunity of implementing electric power systems onboard new-build ships was unlocked.

The purpose of this article was to assess the impact of a new-build electric power system which incorporated advanced technologies such as cold-ironing, photovoltaic (PV) and lithium ion battery systems (hereafter "hybrid system") designed for RoRo cargo ships on the environment, human beings and natural reserves using LCA based on a bottom-up integrated system approach. The study presented in this article did not duplicate the previous case study [54] but extended existing knowledge of LCA studies on marine power systems. The power system presented in [54] and the hybrid system assessed in this case study were different in terms of configuration designs, prime mover types, the connection between prime movers and propellers, and sources of main and auxiliary power supply, to name but a few:

- The power system in [54] involved mechanical transmission between the prime movers (i.e. 4 diesel engines) and the propellers which were connected via reduction gearboxes. Mechanical energy required for propulsion was supplied by diesel engines (and the power-take-in systems after the system was retrofitted). Meanwhile, electrical energy required for hotel services was provided by auxiliary generators (as well as cold-ironing, PV, lithium ion battery and power-take-off systems after the system was retrofitted).
- The hybrid system assessed in this case study, as detailed in Section 2.2, involved electrical transmission between the prime movers (i.e. 6 diesel gensets) and the propellers. Electrical energy required for propulsion and hotel services was mainly supplied by the diesel gensets. To enhance the efficiency of the power system, electrical energy supply was supplemented by cold-ironing, PV and lithium ion battery systems.

In compliance with the four phases of LCA as recommended by ISO14040 and 14044 [71,72], the objectives were set to

(i) define goal and scope of the study;
(ii) estimate resources including energy and materials consumed throughout the life cycle based on background information and the optimised modelling results;
(iii) perform impact assessment; and
(iv) interpret results, in which the focus was put on significant impact categories and their main contributors.

The results presented in this article were novel as electric power systems for new-build cargo ships which incorporated advanced technologies (i.e. the hybrid system) had not been assessed from an environmental perspective. Prior to this study, there was no investigation which specified (throughout a 30-year lifespan)

(i) in what quantity resources would be consumed;
(ii) what impact would be added to the environment, human beings and natural reserves;
(iii) which impact categories would be significant and what the primary causes might be; and
(iv) whether or not a hybrid power system would be more environmentally advantageous compared to a conventional system.

The findings were significant as they could be used by the research community, ship owners and regulators for a comparison with power system alternatives as well as decision making. Materials and methods applied in this study were highlighted in Section 2. The section described the concept of LCA, the power system under study, selection of the technologies and background information required for the study. Section 3 presented results and discussion for the case study. It covered LCI results in terms of resources and emissions during individual life cycle phases as well as their main contributors. It also reported LCIA results for individual impact categories, significant contributors and processes. The impact was verified and further interpreted with scenario analysis prior to drawing conclusions in Section 4.

2. Materials and methods

A number of case studies were carried out to assess the environmental impact of marine power systems onboard RoRo cargo ships. They covered conventional (i.e. diesel mechanical), retrofitting (i.e. diesel mechanical which implemented advanced technologies) and new-build (i.e. hybrid which was electric and implemented advanced technologies) configurations. As these configurations were disparate due to design characteristics and technological diversity, only new-build hybrid configuration was reported here. Other case studies were presented separately in several articles for thoroughness and better readability. RoRo cargo ships were chosen as the reference ship type mainly because of data availability – the operational profile provided by the ship owner was complete to allow for energy management analysis and simulation (performed by research partners). The results were used as the input data of the LCA models developed in this study.

2.1. LCA applied in this study

As a widely recognised tool, LCA was chosen and applied consistently in all cases in compliance with ISO 14040 [71] and 14044 [72]. The study involved goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and life cycle interpretation as illustrated in Fig. 1. The iterative processes began with goal definition by sketching out the plan such as reason and application of the study, targeted audience and intention to present a comparative study or disseminate the findings to the public. This was followed by scope definition which preliminarily described the product system under study, its function(s), functional unit and reference flow (if a comparative study was applied), system boundaries, assumptions made, value choice involved, limitations of the study and requirements on the data and quality, together with an outline of LCIA methodologies and impact categories assessed in the study, followed by a description on how LCI and LCIA results were interpreted, in what format the report was presented and whether or not a critical review was involved. The full life cycle of a product system embraced a number of stages

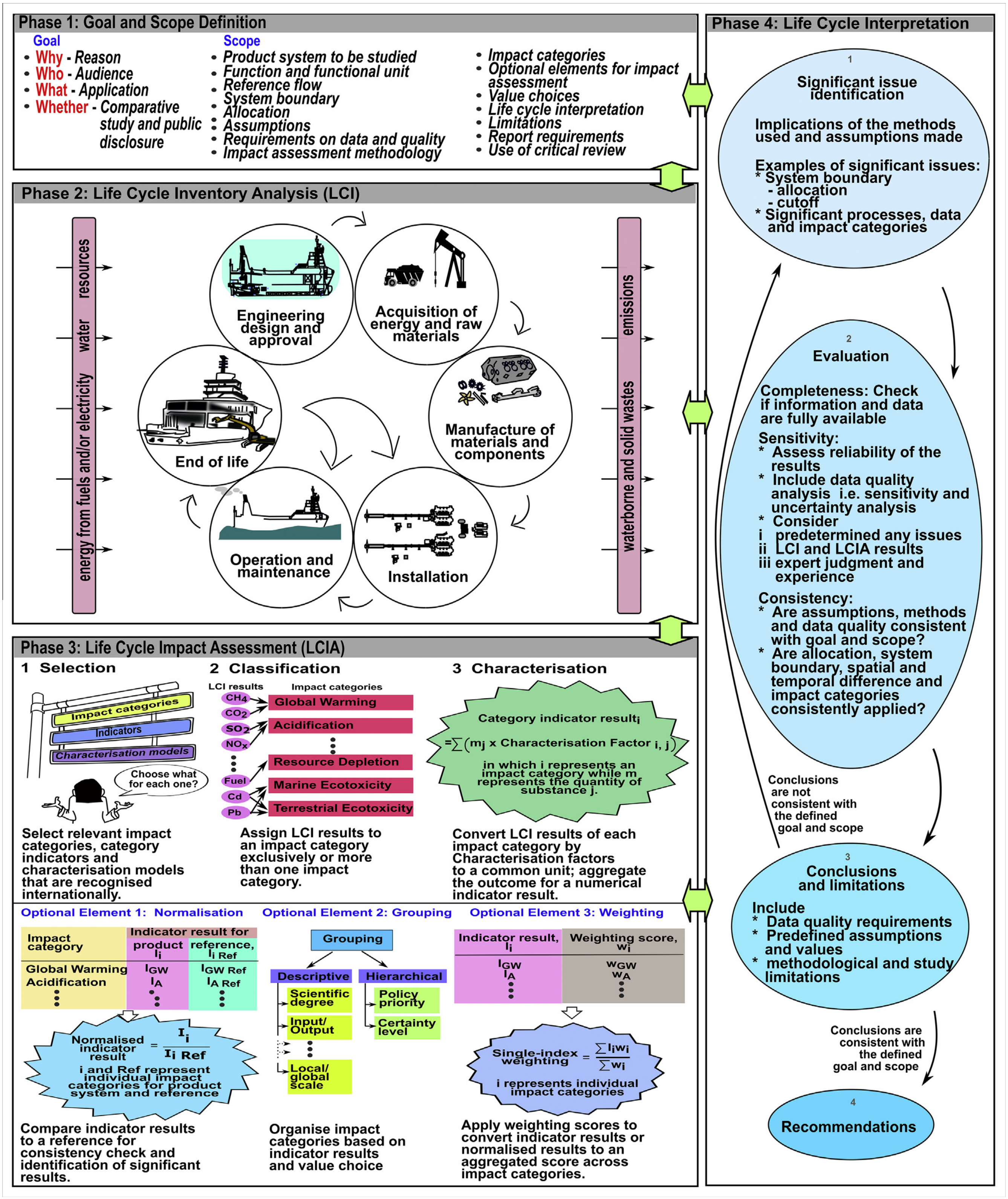

Fig. 1. The four phases of LCA in accordance with ISO 14040 adopted from [54].

such as engineering design and approval, acquisition of energy and materials, manufacture and fabrication, installation, operation and maintenance, and the end of life. Input and output data associated with relevant stages and processes (depending on the defined system boundary) were gathered from various sources and standardised to build up an inventory for life cycle data. The 'outcome of a life cycle inventory analysis' was referred to as 'LCI results', which catalogued 'the flows crossing the system boundary' [72]. LCIA was executed by creating LCA models using commercial software, GaBi (version 6). LCI results were classified to relevant impact categories and category indicator results (i.e. LCIA results) were estimated using selected characterisation models.

Two common LCIA methodologies namely CML2001 and Eco-Indicator99 which represented midpoint and endpoint approaches respectively, and the methodologies recommended by the International Reference Life Cycle Data System (hereafter 'ILCD') were applied. When a natural resource was exploited, the surrounding environment was exposed to physical and chemical changes, and the natural reserve/reservoir dwindled. When an emission was emitted, it dispersed over an area and absorbed by human beings, animals as well as plants via various exposure routes across environmental media such as air, water, food and soil. Such exposure resulted in environmental issues relevant to natural environment, resources and/or human health. The issues were distinguished as a range of impact categories in LCA. All substances showed different potential for individual impact categories. The pathway from resource exploitation/emission distribution to exposure, potential risk or likelihood of imposing an effect, and damage to resources, natural environment and human health was known as an environmental mechanism. Using a midpoint indicator i.e. a point closer to the resource exploitation/emission along the environmental mechanism, a midpoint-oriented characterisation model e.g. CML2001 and ILCD offered discrete indicator results for individual impact categories based on characterisation factors that were derived. On the other hand, an endpoint-oriented characterisation model e.g. Eco-Indicator99 adopted a category endpoint at endpoint/damage level along the environmental mechanism to offer a single score for the damage to resources, natural environment and human health. The mathematic formula used in estimating the indicator result of individual impact categories (I) could be generalised as $I = \sum CF_i\ m_i$, where CF and m represented the corresponding characterisation factor and mass of a substance (i). For midpoint and endpoint approaches, the formula could be presented as $I_{midpoint} = \sum F_{ERi}\ P_{Ri}\ m_{Ei}, i = 0, \ldots, n$ and $I_{endpoint} = \sum F_{ERi}\ P_{Ri}\ S_{ERi}\ m_{Ei}$, $i = 0, \ldots, n$ respectively for n substances distributing across various environmental media (E) via different exposure routes (R), where F was the distribution and exposure of m kg of substance i, P was the potential risk or likelihood of imposing an effect, and S was the severity factor e.g. years of life lost per affected person [73]. Approaches applied in estimating F, P and S varied from one characterisation methodology to another. The mathematical relationships might involve surveys, empirical/experimental data, probability distributions, polynomial functions and numerical/stochastic simulation. This study took advantage of GaBi in which the underlying concepts and mathematical relationships (as detailed in [74–76]) were readily incorporated into the software for applications.

The estimated LCI and LCIA results were interpreted to identify significant issues (i.e. impact categories and contributors) and checked for completeness, sensitivity and consistency with the defined goal and scope. Sensitivity and uncertainty of the results were investigated using scenario analysis. The approach was chosen based on a recent LCA methodology review [53], which reported that scenario analysis had been recognised by the LCA community as an approach used for uncertainty and sensitivity analyses. Advanced statistics such as stochastic and polynomial models were not feasible due to the use of commercial software in this case study. The processes were repeated by refining goal and scope, collecting more data, revising LCI and redoing LCIA until the desired completeness, sensitivity and consistency were achieved. Then, the study was concluded and recommendations were made.

2.2. Description of the power system and selection of the technologies

The hybrid system assessed in this article, as illustrated in Fig. 2, was theoretically designed to supply electrical power required for ship propulsion and hotel services when a RoRo cargo ship was transiting at sea, manoeuvring, mooring and waiting in port. Economic concern was the key factor considered by ship owners in selecting a power system design. Without realising the environmental benefits of hybrid power systems, their commercial applications were unlikely in favour with ship owners. From a technical perspective, the hybrid system would have the advantage of electric power systems i.e. increased capacity, improved manoeuvrability, reduced fuel consumption, boosted system efficiency and enhanced dynamic response as a result of running prime movers at optimum speeds and augmenting power supply via alternative sources. The system, which was technically applicable to other cargo ship types, was jointly proposed by the consortium involved in the project (as credited in the Acknowledgement) through technical collaboration. The system was designed based

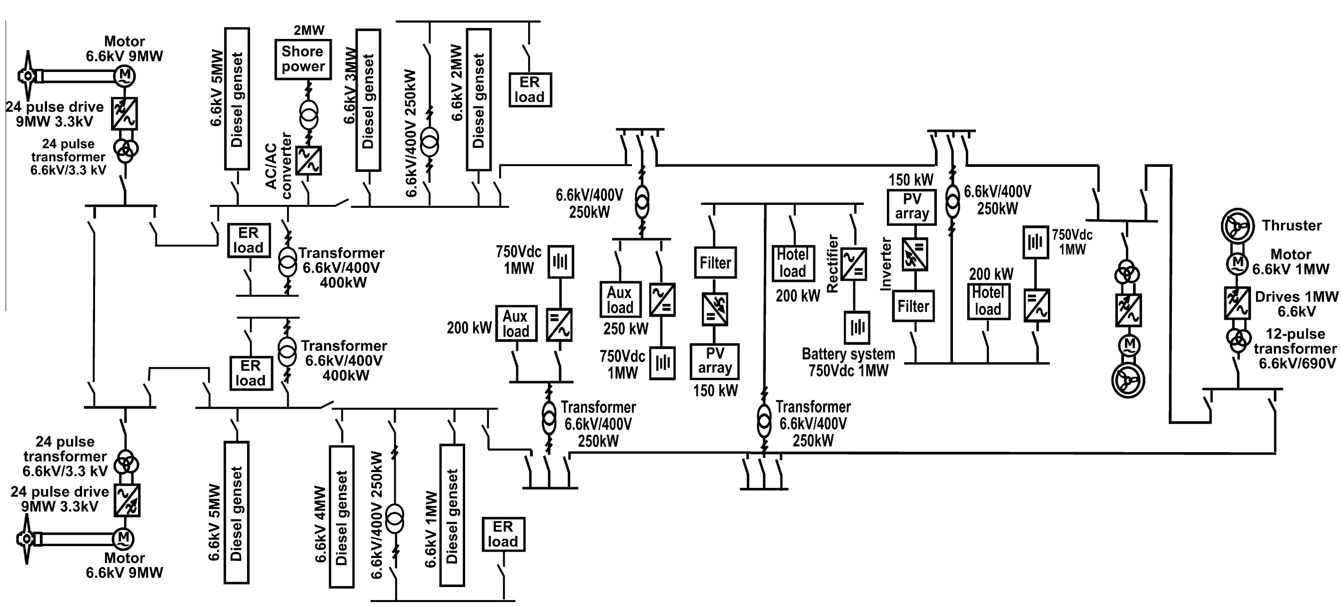

Fig. 2. Single-line diagram of the power system configuration under study (jointly designed by the consortium involved in the technical collaboration work).

on the four interconnected criteria i.e. industry's interest, innovation, technology readiness and sustainability. The design was perceived to have the potential for commercial applications onboard cargo ships, innovative but already ready for implementation with reduced environmental burdens if compared to a conventional diesel mechanical configuration. The system consisted of diesel gensets (acting as prime movers) supplemented by PV and lithium ion battery systems as well as onboard cold-ironing facility (i.e. onshore electricity supply) for hotel services in addition to ship propulsion and manoeuvring via motor-driven propellers and thrusters. The function of the system was enabled by power electronics such as transformers, variable frequency drives (VFDs), AC-AC converters, inverters and rectifiers. For each component, an appropriate model was proposed as summarised in Table 2 covering number, make, speed, power rate, mass and lifespan in consultation with the consortium. The real-time operational data of a RoRo cargo ship which received frequent port calls within ECAs were provided by the ship owner who considered ordering new-build RoRo ships for a business purpose. Details of the RoRo cargo ship included 183 m long, 26 m wide, 6.5 m of draught, 21,171 tonnes of gross tonnage, 12,350 tonnes of deadweight and 3428 m^2 of weather deck area (i.e. the upper deck of the ship which was open and exposed to the weather). Individual technologies were technically investigated by the consortium, as described in [77]. For instance, the PV systems were designed by Offshore Renewable Energy Catapult using industry data and PVSyst software. The PV system design was proposed in line with the space available onboard the ship i.e. 2000 m^2 for the installation of horizontally inclined PV modules. Simulation was performed to determine technical parameters such as the radiance of the sun on a PV surface at different orientation, energy generated and lost during operation. All components were then integrated by the consortium in an energy management model created in General Energy Software (GES) based on Simplex method. The size and the operational profile of the hybrid system (see Section 2.4) were determined in the GES model based on the power demand of the hybrid system, details of the ship, real-time data and the technical outcome of prior analysis.

Table 2
Components incorporated into the configuration design.

Component and function	Details (number, make, speed, power rate, mass and lifespan)[a]
Diesel gensets supplied main and auxiliary power for propulsion and hotel services when the ship was transiting at sea	• Two units of Wärtsilä W9L32E, 5 MW, 47,000 kg, 30 years • One unit of Wärtsilä W8L32E, 4 MW, 43,500 kg, 30 years • One unit of Wärtsilä W6L32E, 3 MW, 33,500 kg, 30 years • One unit of Wärtsilä W6L26, 2 MW, 17,000 kg, 30 years • One unit of Wärtsilä W6L20, 1 MW, 9300 kg, 30 years
PV systems generated power to augment power supply when radiation was sufficient	• Two PV arrays of fixed tilted planes, each consisted of 598 modules manufactured by Kyocera (Type KD245GX-LPB, 245 W_p per module at standard test conditions), 13 modules arranged in series per string for 46 strings occupying 984 m^2 supplying 147 kW_p, 21 kg per module, 30 years • One inverter per array, made by Schneider Electric GT100-208, 300–480 V, 100 kW AC, 1.7 m × 1.2 m × 1.9 m, 1361 kg, 10 years
Lithium ion battery systems stored up surplus energy and supplemented power supply during peak loads when the ship was transiting at sea	• Four phosphate graphite lithium ion battery systems, manufactured by SAFT Speciality Battery Group (referred to as Seanergy® battery system Type LiFePO4 VL 41 M Fe 265 Wh/liter), 8 battery racks contributing to 1 MW h per system, each rack (composed of 14 modules and each module consisted of 14 cells) was 6 m × 8 m × 12–23 m and 750 kg or 560 kg with or without cabinet, 20 years • One unit of Sitras® REC rectifier per battery system, 750 V, 0.8 m × 2.2 m × 1.4 m, 850 kg, 10 years
Cold ironing supplied power from onshore network to avoid running diesel gensets when the ship was in port	• One unit of RESIBLOC® cast-resin transformer with a power of 1000 kVA produced by ABB, 3150 kg with a dimension of 2.08 m × 1.58 m × 2.20 m (inclusive casing), 20 years • One unit of SINAMICS G150-42-2EA3 AC/AC converter, 2150 kW, 3.6 m × 2.0 m × 0.6 m, 3070 kg, 20 years
Propellers which were driven by motors propelled the ship when the ship was transiting at sea	• Two Wärtsilä controllable pitch propellers 4D1190 with a hub diameter of 1.19 m, 59,400 kg, 30 years • Two units of brushless, synchronous propulsion motors made by Hyundai Type HHI/HAN3 245-16, 8900 kW, 15–125 rpm, 3 phases, 16 poles, 110,000 kg, 30 years
Thrusters which were driven by motors navigated the ship during manoeuvring	• Two units of Wärtsilä CT/FT 175 M controllable pitch transverse thrusters, standard design, 60 Hz, 1170 rpm, 995 kW, 5600 kg, 30 years • Two units of squirrel cage, induction thruster motors made by Hyundai Type HHI/HRN7 567-6, 1250 kW, 1200 rpm, 3 phases, 6 poles, 630 V, 60 Hz, 75,000 kg, 30 years
VFDs controlled voltage and frequency input of electric motors	• Two units of ABB MEGADIVE LCI drives A1212-211N465 connecting propulsion motors, air-cooled, 9100 kW, 10,000 kVA, 7000 kg, 15 years • Two units of Altivar ATV1200-A1190-4242 medium voltage VFDs connecting thruster motors, 995 kW, 1190 kVA, 4.06 m × 1.40 m × 2.67 m, 5000 kg, 15 years
Transformers ensured voltage compatibility between components such as the main switchboard and the propulsion drives	• Two units of 24-pulse transformers connecting propulsion motors, each unit consisted of two 12-pulse, dry cast resin transformers made by TRAFOTEK, 6890 kVA, 6600 V, 60 Hz, 3.25 m × 2.56 m × 1.68 m, 10,900 kg, 20 years • Two units of 12-pulse, dry transformers connecting thruster motors, made by TRAFOTEK, 1750 kVA, 6600 V, 60 Hz, 2.63 m × 1.99 m × 1.38 m, 3600 kg, 20 years • Distribution transformers – 2 units of ABB RESIBLOC® transformers, 400 kVA under no load loss condition, 1.66 m × 1.17 m × 1.71 m, 1580 kg (or 1420 kg without casing); 6 units of ABB RESIBLOC® transformers, 250 kVA under no load loss condition, 1.51 m × 1.12 m × 1.66 m and 1220 kg (or 810 kg without casing), 15 years

[a] All details, with the exception of number, were presented for a single unit; models were proposed by industrial consortium.

2.3. Manufacturing processes and mass breakdown of individual components

Manufacturing a product from raw materials involved casting and moulding, forming, separating, conditioning, assembling and finishing (whichever relevant). Details, such as the processes, materials and the quantity required for each, were generally classified by manufacturers as sensitive information. Relevant information presented in product manuals and manufacturers' annual reviews, if any, was incomprehensive. Such information was very limited or not covered at all in existing peer-reviewed journal publications, which would have been the most reliable source. The issue was dealt with by standardising data gathered from alternative sources. They included expert judgement from the industrial consortium, technical reports, textbooks and proceedings in addition to manuals and reviews, as summarised in Table 3.

2.4. The operational profile

In addition to the real-time data, details of the ship and components, other parameters e.g. business route, power demand, maintenance schedule and maximum continuous rating of relevant components were also defined in the GES model. The operational profile which was the outcome of the model predicted the working schedules of the power system for optimal performance. The profile specified, for instance, (i) how the power demand would be met when the ship was transiting at sea, manoeuvring, mooring and waiting in port; (ii) when and for how long a component would be operated at what efficiency rate; and (iii) the rates of fuel consumption and emission, if fuel was burned by a component. As this article focused on the environmental implications instead of energy management, only the operational profile was briefly elaborated here. At sea, three or more gensets and at least one propeller were run for power generation and ship propulsion respectively. With sufficient radiation during day time, energy was generated by PV systems. The generated power was taken and distributed by a main switchboard via distribution bus bars to meet power demand of all consumers for propulsion, hotel loads, heating, ventilation, cooling etc. Surplus energy was stored up by battery systems which supplemented power supply during peak loads. Thrusters were in operation during manoeuvring and mooring while power demand was met mainly by running two gensets.

Table 3
Manufacturing processes and mass breakdowns of components applied in this study.

Components	Manufacturing processes[a]	Materials[b]
Diesel gensets	1. Machining and testing engine block, crankshaft, camshaft and connecting rods 2. Manufacturing other components e.g. pistons, cylinders, cylinder heads etc. 3. Incorporating all components with smart tooling	69.5% cast iron, 21.3% steel, 2.7% aluminium, 2.2% carbon and 1–4% chromium and tin
Propellers and shafts	1. Preparing cast mould 2. Mixing molten raw materials and removing impurity 3. Casting, finishing and assembling blades and hub	3.84% aluminium, 32.32% copper, 0.01% lead, 0.35% manganese, 1.70% nickel, 0.04% silicon, 61.66% steel and 0.04% zinc
Thrusters	1. Preparing cast mould 2. Mixing molten raw materials and removing impurity 3. Casting, finishing and assembling blades and hub	6.75% aluminium, 59.52% copper, 0.02% lead, 3.38% nickel, 0.08% silicon, 28.60% steel, 0.08% tin and 0.75% zinc
Electric motors	1. Producing metal sheet laminations and welding 2. Machining the stator core, rotor and housing 3. Forming electromagnetic circuit for the stator and final assembly	82% steel, 11% copper, 3% cast iron, 1% stainless steel, 1% aluminium, 2% plastic and rubber
Lithium ion battery systems	1. Producing lithium carbonate from lithium rich brine water and soda crystals 2. Washing, drying and mixing lithium carbonate with a solvent to be used in a press 3. Forming cathode and anode by pressing aluminium sheet with lithium ink and copper winding respectively; and 4. Arranging cathodes, anodes, separators and electrolytes systematically to form battery racks	15–30% lithium iron phosphate cathodes, 10–25% lithium intercalation in graphite anodes, 10–20% electrolyte, 3–5% ethylene or propene separator, 1–20% aluminium cathode foil, 1–30% copper anode foil and 20–40% steel case
PV systems	1. Producing and purifying silicon 2. Fabricating solar cells including surface preparation, p-n junction formation, coating and metallisation for electrical conductivity 3. Encapsulating modules (i.e. soldering and laminating tempered low iron glass, ethylene-vinyl acetate (EVA), solar cell and back sheets in series) prior to fitting with aluminium frames and junction boxes	74.16% glass, 10.3% aluminium, 6.55% EVA, 3.48% silicon, 3.60% plastic back sheets, 0.57% of copper, 0.08% of silver, 0.14% of tin and 0.035% of lead
Power electronic such as inverters, rectifiers and converters	1. Producing electronic components and printed circuit board (PCB), which involves lapping, diffusion, photolithography, alloying, evaporating, passivation and encapsulation 2. Installing required electronic components on PCB, soldering and final assembly	6.69% aluminium, 26.34% copper, 46.85% steel, 6.48% inductor, transistor, capacitor and diode, 1.20% corrugated board, 1.43% polystyrene and 0.3% polyethylene
VFDs	1. Producing diodes, capacitors, transistors etc., which involves lapping, diffusion, photolithography, alloying, evaporating, passivation, encapsulation and epoxy filling (whichever relevant) 2. Installing and soldering required components 3. Final assembly	50.52% aluminium, 10.94% steel, 9.97% copper, 2.31% epoxy resin, 2.76% glass, 1.74% butyrolactone, 1.04% nylon, 1.07% polypropylene, 0.71% polyvinylchloride and 18.95% corrugated board
Transformers	1. Producing, cutting, stacking and laminating the core, followed by winding and drying 2. Producing tanks and assembling accessories	44.64% ferrite or aluminium, 9.37% copper, 0.44% steel, 33.02% epoxy resin and 12.51% plastic

[a] All processes began with proposing and approving engineering design and ended with testing, painting and shipping.
[b] Standardised based on inputs from various sources including industrial consortium members.

The ship was connected to onshore power which supplied electricity for hotel services, cargo equipment, deck machinery and battery charging when the ship was waiting in port for unloading/loading cargos before the following journey. Electric motors and power electronics were in use in line with their connecting propellers, thrusters, gensets, onshore power supply, PV or battery systems. Marine diesel oil (MDO) was the only fuel type burned by gensets.

2.5. The end of life phase – dealing with scrap

After 30 years in operation, the system would be out of life. Individual components would be detached from the system for reuse, recycling or disposal. In this study, data for the end of life processes of metallic scrap were mainly derived from literature as summarised in Table 4. They were supplemented by relevant data in Ecoinvent database (version 2.2) which were not detailed here due to the terms of use. For non-metallic scrap, relevant Ecoinvent datasets were adopted.

3. Results and discussion

3.1. Goal and scope definition

The reason of conducting this LCA study was to assess the environmental impact of a new-build hybrid system proposed for RoRo cargo ships which would be travelled within ECAs with frequent port calls. Its application was to support research development and provide information to marine stakeholders and LCA community (which were the targeted audience) on the selected emerging marine system design. The new-build hybrid power system was the product system of this case study. The application was made based on the estimates of resources consumed and emissions released by the power system. The key elements presented to the targeted audience included the identification of significant impact categories and their main contributors. The findings were intended to be disseminated as widely as possible to reach all stakeholders and general public members. The results would assist regulators and ship owners in their decision making and provide a reference for a comparative study in future. The function of the product system was to supply power to all consumers onboard a RoRo cargo ship for 30 years. It was neither pragmatic nor appropriate to adopt one kilogram of a material consumed, one kilogram of a final component produced, one kilowatt-hour of electricity generated or one tonne of cargos shipped over one kilometre as the functional unit of this study. Such definitions were only appropriate provided the system boundary of the LCA study was small with a limited number of components defined as the product system. Taking replacement components into account, 68 individual components and 10 systems as summarised in Table 2 were incorporated into the power system assessed in this study. This could be further justified by the diversity of technologies and components incorporated into the power system in terms of

Table 4
Recycling processes of metallic scrap and data applied in this study.

Scrap types and recycling processes	Energy and emission data standardised from literature for handling 1 kg of each scrap type
Iron and steel scrap: The scrap was mixed with lime (to ease the solder process) and loaded in baskets [78]. In an electric arc furnace (EAF), anodes were submerged and energy was applied to melt the scrap and form liquefied steel. Oxygen gas was constantly supplied to oxidise impurities such as aluminium and silicon into slag	1.705 MJ and 0.618 MJ of energy provided by electricity and burning natural gas respectively, 0.015 kg pig iron and 0.0399 kg liquid oxygen were required, which released 0.000102 kg sulphur dioxide (SO_2), 0.00024 kg nitrogen oxides (NO_x), 0.105 kg CO_2, 0.0024 carbon monoxide (CO), 0.0159 kg particulate matter 2.5 ($PM_{2.5}$), 0.000201 kg particulate matter 10 (PM_{10}) etc. [78,79]
Stainless steel scrap: After melting stainless steel scrap in an EAF (in a similar manner to recycling steel scrap), the molten stainless steel was further processed in an argon-oxygen decarburising furnace to remove impurities [80,81]	7.175 MJ and 2.6 MJ of energy provided by electricity and burning natural gas respectively, 0.063 kg pig iron and 0.167 kg liquid oxygen were required, which released 0.000428 kg SO_2, 0.00000827 kg NO_x, 0.441 kg CO_2, 0.0101 kg CO, 0.0671 kg $PM_{2.5}$, 0.000846 kg PM_{10} etc. [79,82]
Aluminium scrap: The scrap was preheated and treated in open loops to remove contaminants, coating and grease before being melted in a rotary furnace. Other common chemical treatments in practice were filtering, fluxing and floating, which removed alumina, impurities and hydrogen respectively. The molten aluminium was cast as secondary ingots or turned into alloys [83,84]	0.0953 MJ and 10.223 MJ of energy provided by electricity and burning natural gas respectively was required to produce 0.883 kg aluminium ingot, which released 0.00441 kg SO_2, 0.00265 kg NO_x, 0.545 kg CO_2, 0.000883 kg CO, 0.000883 kg PM etc. [85–87]
Copper scrap: The scrap containing 92–95% of copper was smelted in an anode furnace and then oxidised by air blow to remove impurities [80,87]. To recycle copper alloy scrap with less than 70% of copper content (including brass scrap), the scrap was smelted in a blast furnace and oxidised in a converter prior to electrolysis.	4.95 MJ of energy provided by burning blast furnace gas was involved, which released 0.00002 kg SO_2, 0.00007 kg NO_x, 0.2 kg CO_2, 0.000015 CO, 0.00019 kg $PM_{2.5}$, 0.00026 kg PM_{10} etc. [79,87,88]
Zinc scrap: Close-loop recycling was only applied for metallic scrap from alloys containing zinc, e.g. brass and bronze, where the scrap was melted with other metals to produce the alloy [89]. If it was aimed to recover other metals in addition to zinc from the scrap, the scrap could be heated in a basket placed in a molten salt bath where liquid metal was collected at a sequence of temperatures. To recover zinc coat from galvanised steel scrap, electrolysis and leaching was applied	0.733 MJ, 0.335 MJ and 1.455 MJ of energy provided by electricity, burning natural gas and coal were required, releasing 0.00367 kg SO_2, 0.00157 kg NO_x, 0.0000394 kg $PM_{2.5}$, 0.00000756 kg PM_{10} etc. [87]
Lead scrap: Industrial and other lead scrap, which were in small quantity, was generally used in producing alloys or new batteries. Slag containing lead could be used as materials for cement industry or disposed to landfill as solid waste [90]. To further enhance the level of purity and remove impurities, raw lead produced from smelting process could be refined via electrolysis or melting in refining kettles	7 MJ of energy provided by burning blast furnace gas was required, which released 0.00002 kg SO_2, 0.00007 kg NO_x, 0.2 kg CO_2, 0.000015 kg CO, 0.0079 kg $PM_{2.5}$, 0.0106 kg PM_{10} etc. [79,87,90]
Nickel scrap: 57% of nickel scrap was recycled as stainless steel scrap, 14% as carbon and copper alloy scrap and 21% was disposed to landfill [91]. If recycled, the process would start with degreasing the scrap, mixing with virgin material, being melted in an induction furnace and then cast under vacuum or with argon blow to form solid ingots	1.920 MJ, 0.215 MJ, 2.298 MJ and 1.709 MJ of energy provided by electricity and burning heavy fuel, coal and natural gas respectively were required, and releasing 0.0119 kg CO_2, 0.000295 kg $PM_{2.5}$, 0.0000429 kg PM_{10} etc. [79,87]

(i) lifespans i.e. from 10 to 30 years;
(ii) functions e.g. transformers adjusted voltage of the current, propellers navigated the vessel and thruster motors rotated the connecting thrusters for manoeuvring, to name but a few; and
(iii) power capacity, which involved mechanical, electrical and/or thermal energy.

Also, the environmental burdens of a marine vessel would vary, for instance, in terms of magnitude with vessel types, power system designs, technologies, fuel types and sailing profiles. Therefore, the functional unit should be more comprehensive at a system level. The operation of the hybrid power system implemented onboard a RoRo cargo ship travelling on regular routes within ECAs over a lifespan of 30 years was set as the functional unit. Acquiring raw materials and energy, manufacturing, operating, maintaining, dismantling and handling end-of-life scrap of all components incorporated into the system (as presented in Fig. 2 and Table 2) were defined as the system boundary. Replacing some technology components was necessary because of their shorter lifespans. To avoid allocation, system expansion was applied to include these additional units as a part of the system boundary.

It was assumed that

(i) the cargo ship would operate within ECAs with the fixed business route;
(ii) without retrofit, the power system would operate to meet the power demand onboard the cargo ship ranging between 1250 kW and 9033 kW, as illustrated in the supplementary material (Appendix 2), over 30 years experiencing no malfunction;
(iii) materials used in manufacturing power electronics such as inverters, rectifiers and converters and their processes were similar, as did 24-pulse, 12-pulse and distribution transformers;
(iv) components of old diesel gensets could be reused if remained in good condition, and therefore the scrap was 30% reused, 30% recycled, 20% disposed to incineration plants and the remaining was disposed to landfill (as modelled in the base case);
(v) metallic scrap of other technology components would be equally recycled, disposed to incineration plants or landfill; and
(vi) the power system was a closed-loop product system where the use of materials recovered from the end of life processes was not further assessed.

In practice, the product system could only function appropriately and safely with the use of ancillaries such as a main switchboard, bus bars, circuit breakers, fuses, wires, fuel oil systems, pipings and an emergency power supply system. However, such devices were not assessed here. Engineering design and approval, installation, material loss during manufacture, transportation, spatial and temporal specific data, and changes in future technology were also beyond the scope. Altogether, they presented limitations of this case study. The exclusion was necessary due to limited resources, the already complicated scope (without taking account of ancillaries), and their relatively negligible impact if compared to the currently defined product system.

In principle, data of primary sources (i.e. on-site, first-hand input/output data recorded by ship owners and operators at real manufacturing plants and end of life management facilities) and high quality (in particular those reported in journal articles) were preferable. However, such data were expensive and not readily available. The requirements on data and their quality were therefore compromised by adopting data from other sources to make the first move to offer insights in this matter. Expert judgement from industry, although subjective, was valuable in this case study as the recommendations were made based on day-to-day working experience. The findings could be revisited and refined in future work when data of higher quality were available.

Value choices were involved not only in selecting the ship type and technologies based on technical consideration and expert judgement from the consortium but also in determining the characterisation models applied in the study. Normalisation, grouping and weighting were not performed to allow comparison with alternative systems in future. In performing life cycle interpretation, significant issues, such as components and processes which resulted in noticeable environmental burdens, were identified. The results were checked for completeness and consistency with the defined goal and scope. Focussing on significant impact categories and contributors, scenario analysis was applied to check for sensitivity and reliability of the results.

3.2. LCI results

LCI results presented in this section focused on resource consumption and emissions. The LCI results were necessary to support the application of this LCA case study and ensure consistency with the defined goal and scope of the study. As illustrated in Fig. 3(a), a selection of materials ranging 1–5 orders of magnitude would be required in manufacturing components that were incorporated into the hybrid power system. In descending order, steel, cast iron, copper and aluminium were estimated as the top four most commonly consumed materials i.e. 4.52×10^5 kg, 1.48×10^5 kg, 1.11×10^5 kg and 9.03×10^4 kg respectively. The main constituents of these materials would be used in manufacturing diesel gensets, propellers and shafts, propulsion motors and the connecting drives as well as transformers, and thruster motors. Significant usage included

(i) 16.2%, 27.3% and 40.0% of steel for propellers and shafts, thruster motors and propulsion motors respectively;
(ii) 92.5% of cast iron for diesel gensets;
(iii) 14.9%, 21.8% and 34.6% of copper for thruster motors, propulsion motors and propellers and shafts respectively; and
(iv) 15.7% and 43.1% of aluminium for the drives and transformers that connected to propulsion motors.

During the processes, 4.15×10^3 MJ, 3.15×10^5 MJ, 8.86×10^5 MJ and 2.24×10^5 MJ of energy would be provided, respectively, by furnaces which burned heavy and light fuel oils respectively, boilers which burned natural gas and electricity directly. Among all, manufacturing propellers and shafts, thruster motors, diesel gensets and propulsion motors would use up approximately 13%, 16%, 22% and 24% of the energy provided by furnaces and boilers. Meanwhile, approximately 75% of electricity would be required for manufacturing thruster motors, diesel gensets, propulsion motors and PV systems, accounting for 12.3%, 16.1%, 18.0% and 27.9% respectively. In terms of the two largest non-metallic material types being utilised, 70.0% of epoxy resin and 93.4% of glass would be consumed during the processes of manufacturing transformers connecting propulsion drives and PV systems respectively. With consultation from industrial consortium members involved in this study, it was estimated that 9.46×10^4 kg of lubricating oil would be required in maintaining diesel gensets, propellers, thrusters and motors regularly over the lifespan for optimum performance. To treat and recover used lubricating oil, 1.91×10^2 kg of light fuel oil, 2.29×10^2 kg of liquefied petroleum, 2.54×10^2 kg of diesel, 4.38×10^5 MJ of heat supplied by burning natural gas and 4.92×10^6 MJ of energy supplied by

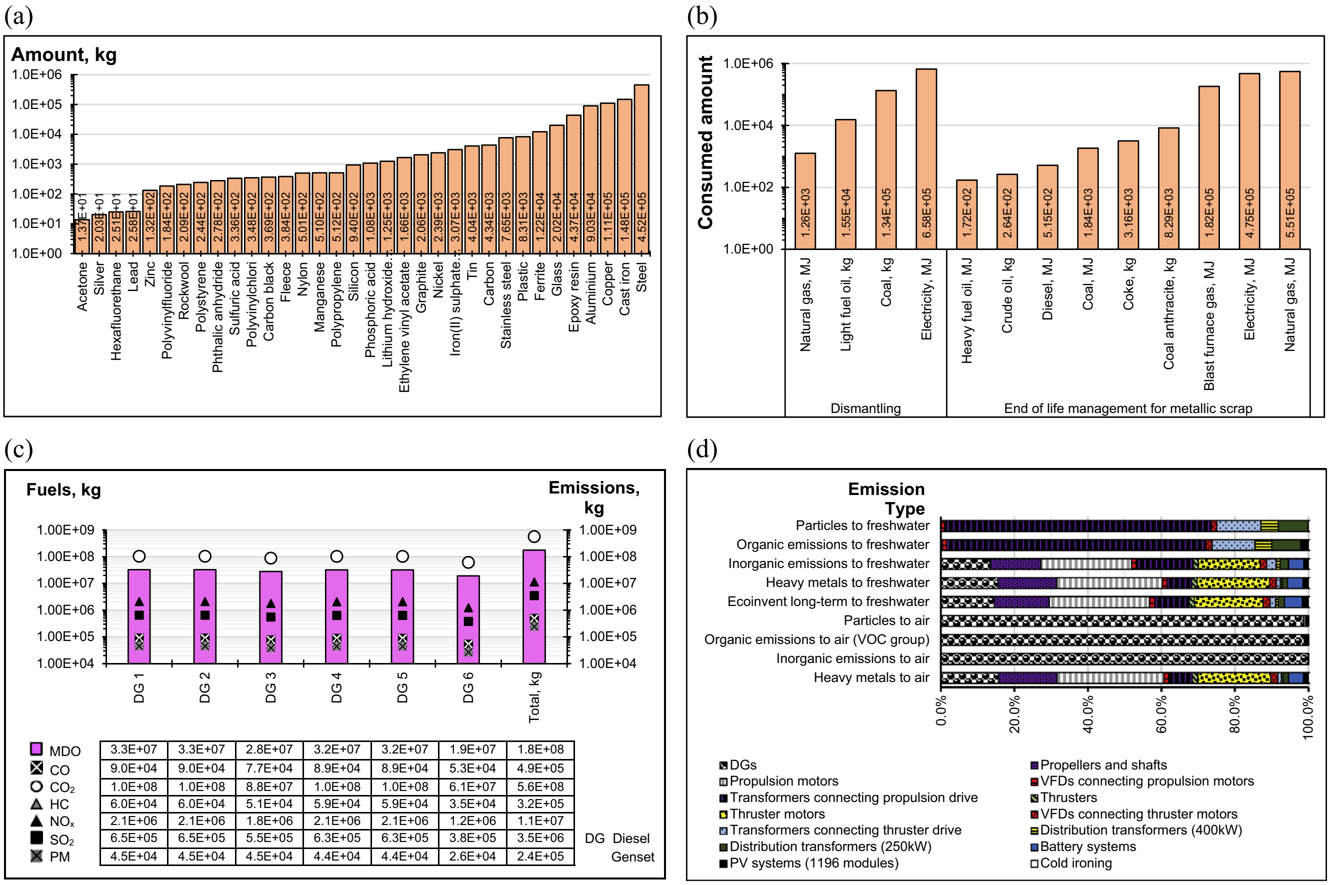

Fig. 3. (a) Materials used in manufacturing components incorporated into the hybrid power system, in kg; (b) resource and energy consumed during dismantling and end of life phases; (c) fuel consumed and emissions released during operation over 30 years; and (d) emissions of the hybrid power system from acquisition of raw materials and energy to end of life management as per individual technologies, which were estimated via LCA models developed in GaBi for the base case scenario.

electricity would be needed. Likewise, 6.58×10^6 MJ of electricity and 5.51×10^6 MJ of heat supplied by burning natural gas were reported as the largest energy sources to be consumed in dismantling the power system and handling the scrap, as illustrated in Fig. 3(b).

The operation of diesel gensets over 30 years would burn 1.76×10^8 kg of MDO, which in turn released 4.87×10^5 kg of carbon monoxide (CO), 5.60×10^8 kg of CO_2, 2.43×10^5 kg of PM, 3.25×10^5 kg of hydrocarbons (HC), 1.13×10^7 kg of NO_X and 3.49×10^6 kg of sulphur dioxide (SO_2) as illustrated in Fig. 3(c). In the context of LCA, environmental compartments included air, freshwater, sea water, sediment, industrial and agricultural soil. From a life cycle perspective, emissions from the hybrid system would be mainly released to air and freshwater: (i) 1.89×10^4 kg of heavy metals, 2.51×10^5 kg of particles, 3.30×10^5 kg of organic emissions (volatile organic compounds (VOC) group) and 5.76×10^8 kg of inorganic emissions to air; and (ii) 2.52×10^2 kg of organic emissions, 1.14×10^3 kg of heavy metals, 3.31×10^3 kg of particles, 3.25×10^5 kg of Ecoinvent long-term emissions and 5.26×10^5 kg of inorganic emissions to freshwater. Emissions to sea water and sediment were marginal because most emissions were released to the air when the ship was at sea or in port. Emissions to industrial and agricultural soil were also negligible as the lifespan of the ship was largely spent for operation, at sea and in port. Contributions of individual technologies towards emissions to air and freshwater were illustrated in Fig. 3(d) based on LCI results estimated using GaBi models. For emissions released to air, diesel gensets were the primary contributors, accounting for approximately 99% of particles, organic and inorganic emissions respectively. Heavy metals released to air due to thruster motors and propulsion motors were significant (i.e. 19.8% and 29.1% respectively), together with diesel gensets as well as propellers and shafts (each resulted in approximately 16%). In relation to organic and particle emissions to freshwater, transformers connecting propulsion motors played a significant role and were accountable for 70.6–72.6%. A more balanced distribution was observed for inorganic, heavy metals and ecoinvent long-term emissions to freshwater, in which the major contributors were propulsion motors (24.7–28.8%), thruster motors (16.9–19.6%), diesel gensets (13.4–15.6%) as well as propellers and shafts (13.8–15.9%). Other technologies including PV and battery systems were accounted for 1.0–4.6% each, with the exception of transformers connecting propulsion drives (6.7–15.5%).

Electricity was consumed throughout the lifespan of the hybrid system. During manufacture, operation when the ship was in port and the end of life, onshore electricity demand was supplied from more than one source. The electricity mix and emissions released from onshore power generation were included in the LCA models of individual components using Ecoinvent datasets directly. When the ship was at sea, emissions were released as diesel gensets burned MDO to generate electricity. Such emissions were incorporated into the LCA models as the output flows of diesel gensets in operation. The analysis showed that onshore electricity demand and emissions released during manufacture, operation when the ship was in port and the end of life phase were relatively insignificant when compared to those of the operation phase when the ship was at sea. The findings were in agreement with the length of time spent by the hybrid system for individual life cycle phases and the low auxiliary power demand when the ship was in port, i.e. 650 kW. Accordingly, the influence of onshore electricity mix over total emissions released by the hybrid system throughout its full life cycle was not substantial.

3.3. LCIA results

To date, none of the existing LCIA methodologies has fully incorporated all impact categories that were relevant to the marine context. An impact assessment using more than one methodology was therefore necessary for comprehensive understanding. In this case study, CML2001, ILCD and Eco-Indicator99 were applied where relevant impact categories were scrutinised. Whilst CML2001 differentiated marine, freshwater and terrestrial ecotoxicity potential as well as estimated human toxicity potential, ILCD distinguished between marine and terrestrial eutrophication potential and was more relevant for the European context. Eco-Indicator99 complemented the assessment in a similar line of thought with [92,93], which advocated that both midpoint and endpoint approaches should be consistently presented in series or parallel in an LCA framework (i.e. an LCA application in this case study). Provided only a single impact assessment methodology was applied, some relevant impact categories would be omitted inevitably.

The LCIA results and contributions of individual technologies towards individual impact categories (which were labelled as I–XXVI for brevity) were illustrated in Fig. 4(a) and (b). The most significant impact categories assessed by CML2001, ILCD and Eco-Indicator99 were not of the same kind i.e. *Marine Aquatic Ecotoxicity Potential*, *Ecotoxicity for Aquatic Freshwater* and *Ecosystem Quality – Acidification/Nutrification*. The estimated LCIA results were 5.92×10^{10} kg 1,4-dichlorobutane (DCB) equivalent, 1.39×10^{10} comparative toxic unit for ecosystems (CTUe) and 6.81×10^{7} potentially disappeared fraction (PDF) $* \, m^2 * a$ respectively. Such disparity was mainly because of the adoption of diverse environmental mechanisms and mathematical relationships by these characterisation methodologies. Nevertheless, the orders of magnitude for the most significant impact categories assessed by both CML2001 and ILCD were in agreement, indicating 3 orders of magnitude more burdensome than that assessed by Eco-Indicator99. The majority of the impact categories were in the range of 3–7 orders of magnitude. The least significant impact categories assessed by CML2001, Eco-Indicator99 and ILCD respectively i.e. *Abiotic Depletion of Elements*, *Human Health – Climate Change* and *Resource Depletion, Fossil and Mineral, Reserve Based* were of 2 orders of magnitude.

With identified significant contributors and processes, correlations between impact category types and technologies were observed. Half of the impact categories (labelled as III–IV, VI, IX, XII–XIII, XV–XVIII, XX–XXI and XXVI in Fig. 4) were relevant to PM/respiratory inorganic health issues, photochemical ozone creation, eutrophication, acidification and global warming. Diesel gensets were nearly fully accountable for these impact categories i.e. more than 99.0%, predominantly caused by their operation. The other half (labelled as I–II, V, VII–VIII, X–XI, XIV, XIX and XXII–XXV) covered human toxicity, ecotoxicity, resource depletion and consumption. Again, operating diesel gensets was found as the main process which resulted in human toxicity. In relation to ecotoxicity, disposing metallic scrap to incineration plants was significant, in which diesel gensets were accountable for 15.5%. Due to tin and chromium consumption during manufacture and fossil consumption during operation, diesel gensets also contributed remarkably towards a few impact categories i.e. approximately 93% of LCIA results estimated for Eco-Indicator99: *Resources – Minerals*; and 69.4–71.9% for (i) CML2001: *Abiotic Depletion*, (ii) CML2001: *Terrestric Ecotoxicity Potential*, (iii) ILCD: *Resource Depletion, Fossil and Mineral, Reserve Based* and (iv) Eco-Indicator99: *Ecosystem Quality – Land-Use*. Nevertheless, technologies including propellers and shafts, and their connecting motors and transformers as well as thruster motors showed a noteworthy effect for the remaining impact categories. Approximately 62% of the LICA results for (i) CML2001: *Abiotic Depletion of Fossil* and (ii) Eco-Indicator99: *Resources – Fossil Fuels* were caused by transformers connecting to propulsion drives, mostly due to the production of epoxy resin liquid used in the manufacturing phase. In relation to (i) CML2001: *Freshwater Aquatic Ecotoxicity Potential*, (ii) CML2001: *Marine Aquatic Ecotoxicity Potential*, (iii) ILCD: *Total Freshwater Consumption, Including Rainwater, Swiss Ecoscarcity*, (iv) ILCD: *Ecotoxicity for Aquatic Freshwater, USEtox (recommended)* and (v) Eco-Indicator99: *Ecosystem Quality – Ecotoxicity*, contributions from propellers and shafts, propulsion motors and thruster motors ranged 15.8–17.3%, 21.8–28.8% and 14.9–19.6% respectively, in which disposing metallic scrap of these components to incineration plants was the main cause. Other technologies including VFDs, distribution transformers, battery systems, PV systems and cold-ironing contributed to the environmental burdens to such an extent that they were relatively negligible when compared to diesel gensets, propellers and shafts, propulsion motors and thruster motors, in spite of resources being consumed and operation over the same period of lifespan.

To justify the environmental benefits of the hybrid system, the estimated LCIA results were compared to those of a diesel mechanical power system which would deliver the same function onboard a RoRo ship over 30 years. The diesel mechanical power system was the conventional design commonly employed onboard cargo ships. The conventional system was adopted from [54] which was referred to as 'the business as usual scenario' and used to verify the environmental benefits of the power system assessed in that study. The conventional system, i.e. 549,960 kg in total, consisted of 4 diesel engines connecting 2 shaft generators and 2 gearboxes that driving 2 propellers, which were supplemented by 2 thrusters for ship propulsion and 2 auxiliary generators, 4 boilers and 4 economisers for hotel services. By comparing with the conventional system, it was found that throughout the lifespan, the hybrid system would result in heavier burdens to the environment in terms of ecotoxicity potential, as illustrated in Fig. 5. These included CML2001: *Freshwater Aquatic Ecotoxicity Potential*, CML2001: *Marine Aquatic Ecotoxicity Potential*, ILCD: *Ecotoxicity for Aquatic Freshwater* and Eco-Indicator99: *Ecosystem Quality – Ecotoxicity* (labelled as VIII, X, XIX and XXV respectively). The estimated increases were 1.41×10^{8} kg 1,4-DCB equivalent, 2.81×10^{10} kg 1,4-DCB equivalent, 6.71×10^{9} kg CTUe and 1.79×10^{7} PDF $* \, m^2 * a$ respectively, which were equivalent to 90.0–93.9% of such impact of the conventional system. The comparison was made using LCIA results for the base case scenarios of both systems, which adopted the same reuse-recycling-incinera tion-landfill ratio. Disposing metallic scrap was the critical process, which led to ecotoxicity potential in both cases. For the conventional system, diesel engines, auxiliary generators, propellers and shafts were accountable for approximately 90% of the impact. For the hybrid system, approximately 79% of the impact was due to diesel gensets, propellers, propulsion motors and thruster motors whilst the remaining was contributed by other components such as transformers, thrusters, VFDS, cold-ironing, PV and battery systems. As the total mass of the hybrid system was 67.5% more than that of the conventional system, the hybrid system had to dispose more metallic scrap if compared to the conventional system. The 90–93% of increase in the impact of the hybrid system was therefore justifiable when the same reuse-recycling-incineration-land fill ratio was applied in the base case scenarios. The magnitude would be lessened provided more scrap was reused, recycled or disposed to landfill. Due to the additional mass of the hybrid system, more natural gas, light and heavy fuel oil was required during

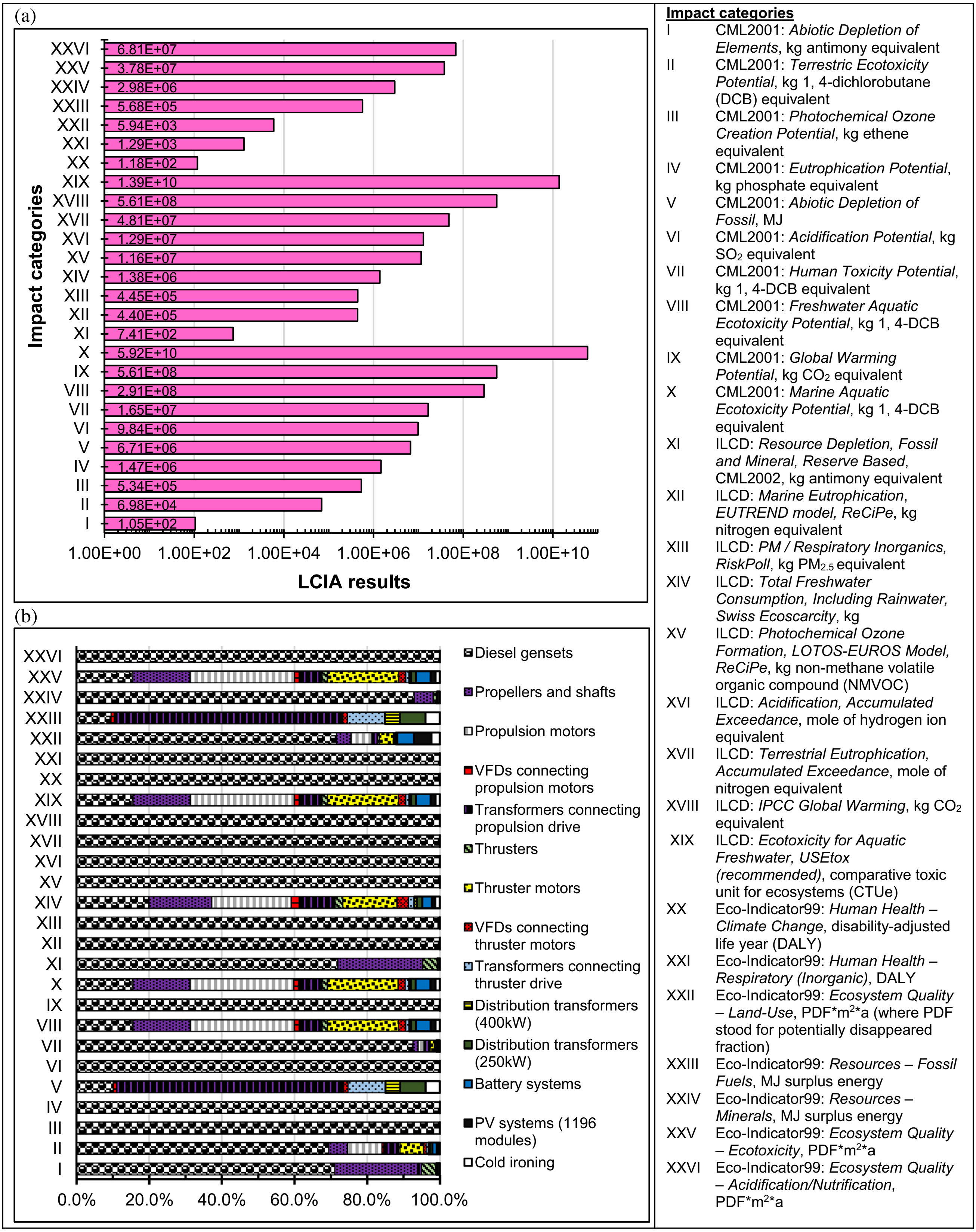

Fig. 4. (a) Total environmental burdens attributable to the new-build power system, characterised as per impact categories and (b) contributions of individual components towards individual impacts.

manufacture, dismantling and the end of life phase. Accordingly, the hybrid system showed a higher LCIA result in CML2001: *Abiotic Depletion of Fossil* and Eco-Indicator99: *Resources – Fossil Fuels* (labelled as V and XXIII). Having said that, other impact categories caused by the hybrid system which were relevant to PM/respiratory inorganic health issues, photochemical ozone creation,

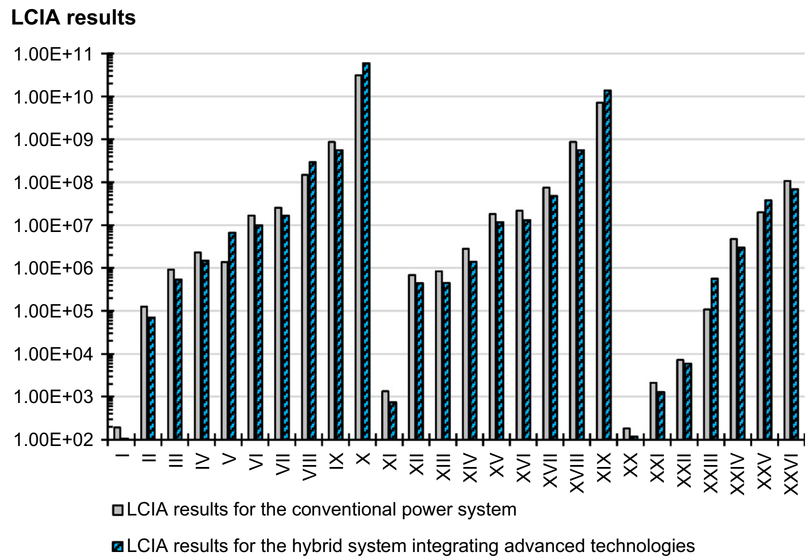

Fig. 5. The LCIA results of individual impact categories estimated for both conventional and hybrid power systems.

eutrophication, acidification, global warming and human toxicity showed a reduction in comparison with the conventional system. The least reduction, i.e. 17.1%, was shown by Eco-Indicator99: *Ecosystem Quality – Land-Use* (labelled as XXII) whilst a 35.7–50.7% of decline was observed in other impact categories. For impact categories with reduced magnitude, a general correlation between significance of an impact category and the magnitude of the reduction was observed: the more significant an impact category was, the more reduction in the magnitude of the impact could be brought by the hybrid system. Reduction across all impact categories would not be possible in practice. Taking all impact categories into account, a comparative assertion could be made: an overall improvement in the environmental performance of a marine power system could be achieved provided the hybrid system as assessed in this study was employed to substitute a diesel mechanical system (i.e. the conventional system). This was indicated by the reduction in 20 impact categories to the detriment of ecotoxicity potential and depletion of fossil fuels. Following the employment of the hybrid system, the LCIA results for all impact categories would vary by 0–1 orders of magnitude. As such, the reduction in 20 impact categories was perceived to outweigh the increase in the other 6 impact categories. It was also worth noting that advanced technologies i.e. cold-ironing, PV and battery systems which were incorporated into the hybrid system had little or no contribution towards individual impact categories (up to 4.8%). Therefore, the environmental benefits brought by the hybrid power system was verified. The life cycle of power systems must be appropriately managed with due care to avoid shifting the burdens from one impact category to another while alleviating the environmental burdens at the same time.

In relation to background data applied in this case study for manufacturing processes, the data were standardised from various sources such as technical reports, text books, manuals as well as expert judgement (as reported in Section 2.3) due to unavailability of high quality data. Taking the whole system into account, the LCIA results of the power system were expected to vary modestly provided the study was repeated with high quality data for manufacturing processes. This was because the manufacturing phase had been found insignificant when compared to operation and the end of life of the power system under study. Following the same train of thought, data for both operation and end of life phases would exert a stronger influence on the LCIA results. Nevertheless, the impact categories were expected to show similar trends in terms of the order of magnitude and their significance. In this matter, the assumptions and limitations of the study would also influence the estimated LCIA results to some extent, minimally, moderately or significantly. Altogether, the assumptions and limitations presented a complex problem. No conclusive remark could be drawn without in-depth investigation. Therefore, the findings should be revised in future with higher quality data, dispelled assumptions and fewer limitations. Power demand and the operational profile would vary because of weather conditions, unstructured business routine, exclusion of the innovative technologies or employment of the system onboard other ship types. Such variation resulted in different levels of fuel consumed and emission released. Consequently, the LCIA results of the impact categories attributable to the power system would alter, in particular those relevant to PM/respiratory inorganic health issues, photochemical ozone creation, eutrophication, acidification and global warming. Following the variation in power demand and the operational profile, changes in other impact categories, which were mainly caused by the end of life management of the power system, were expected to be marginal. From a technical perspective, alternative system designs could also be proposed by integrating different technologies such as WHR, fuel cells and wind propulsion, which would affect the magnitude of the total environmental impact caused by a power system. In all cases, the environmental impact of the hybrid power system presented in this study could be used as a reference for comparison to verify the environment benefits of alternative hybrid power systems. The comparison would provide insightful information to ship owners and assist them in choosing the system to be employed in real life for new-build ships.

3.4. Life cycle interpretation

Throughout the life cycle of the hybrid system, operating diesel gensets and disposing metallic scrap of diesel gensets, propellers and shafts, propulsion motors and thruster motors to incineration plants were identified as the key processes with serious consequences. Both were significant to such an extent that the former largely resulted in 13 impact categories whilst the latter was conspicuously accountable for ecotoxicity – one of the top two most burdensome impact categories assessed by CML2001, Eco-Indicator99 and ILCD. To further investigate these factors, additional scenarios were modelled and the LCIA results were compared to those for the base case scenario (as presented in Section 3.3).

In real-time operation, diesel gensets might be run without strictly following the optimal profile (as modelled in the base case scenario) because of weather conditions, unexpected demand variation, unstructured business routine, to name but a few. Bearing this consideration in mind, diesel gensets in additional scenarios were modelled to burn (i) 10% less; (ii) 20% less; (iii) 30% less; (iv) 10% more; (v) 20% more; and (vi) 30% more fuel than those in the base case scenario; and the differences in LCIA results were illustrated in Fig. 6(a). The following correlations between fuel consumption and impact categories were observed:

- An x% of increase (or decrease) in fuel consumption would lead to an approximately x% of such change in LCIA results of the impact categories that were largely caused by diesel gensets (labelled as III–IV, VI, IX, XII–XIII, XV–XVIII, XX–XXI and XXVI in Fig. 4). A linear relationship was formed. The more fuel was consumed, the more burdensome these impact categories would be. It was worth noting that battery systems, PV systems and cold-ironing were incorporated to lighten the power loads of diesel gensets. Without them, more fuel would be consumed.

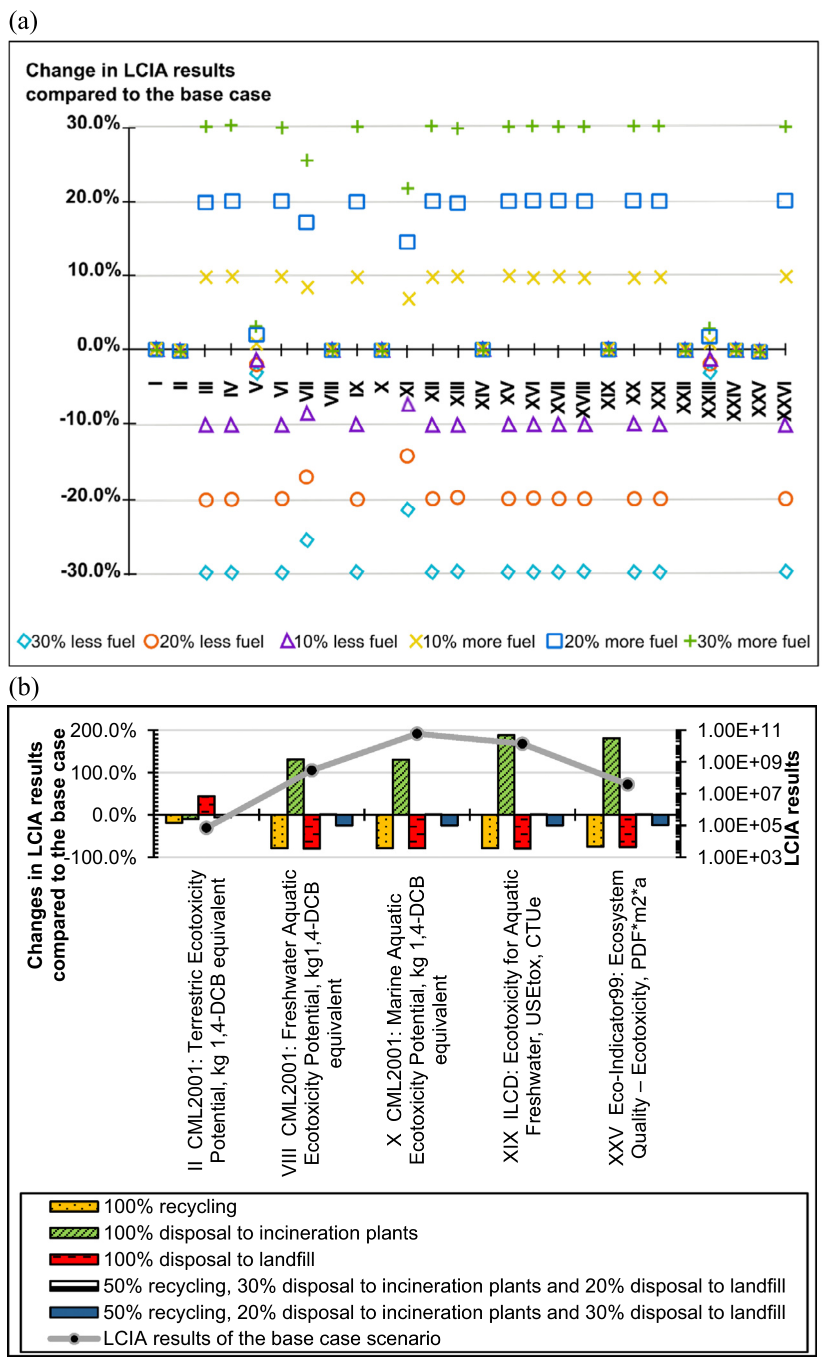

Fig. 6. Changes in LCIA results for (a) all impact categories (labelled as I–XXVI as in Fig. 4) compared to the base case scenario when fuel consumed by diesel gensets was reduced by 10%, 20% and 30% or increased by 10%, 20% and 30%; (b) ecotoxicity potential assessed by CML2001, Eco-Indicator99 and ILCD following theoretical end of life scenarios.

By investigating the scenarios of burning 10%, 20% and 30% more fuel, the benefits of these emerging technologies were justified indirectly too.

- Variation in LCIA results for impact categories related to fossil fuels was dependent on the total contribution of diesel gensets towards such impact. The variation ranged 0.95–3.04% for CML2001: *Abiotic Depletion of Fossil* and Eco-Indicator99: *Resources – Fossil Fuels* (labelled as V and XXIII; 10.14% and 9.54% respectively caused by diesel gensets in the base case scenario) and 7.2–21.6% for ILCD: *Resource Depletion, Fossil and Mineral, Reserve Based* (labelled as XI; 71.9% attributable to diesel gensents in the base case scenario). Thus, the more diesel gensets contributed to these impact categories, the more profound the change in LCIA results would be.
- A unique causal relationship was found between CML2001: *Human Toxicity Potential* (labelled as VII) and fuel consumption. Although the impact was still a function of fuel consumption, the ratio of difference in the LCIA result to the change in fuel consumption was no longer one-to-one due to the influence of other technologies.
- For impact categories relevant to ecotoxicity, mineral and freshwater consumption, (labelled as I–II, VIII, X, XIV, XIX and XXIV–XXV), the influence of changes in fuel consumption was very minimal or no influence at all. This was in agreement with previous analysis which showed that operating diesel gensets was an insignificant cause to these impact categories.

The analysis indicated that the impact attributional to the power system would vary with fuel consumed by diesel gensets significantly, less pronouncedly or very minimally, depending on the overall contribution of diesel gensets towards individual impact categories.

In relation to the end of life phase of components incorporated into the system, the extent to which they were reused, recycled and disposed to incineration plants or landfill in reality was uncertain. In the base case scenario, a reuse-recycling-incineration-land fill ratio of 3:3:2:2 was adopted for diesel gensets while for other components, 33.3% of metallic scrap was recycled, disposed to incineration plants or landfill respectively. Considering that theoretical analysis could provide insights into the nature of this complex matter, additional scenarios were modelled (with a focus on diesel gensets, propellers and shafts, propulsion motors and thruster motors which were found significant as reported in Section 3.3). The additional scenarios covered (i) 100% recycling; (ii) 100% disposal to incineration plants; (iii) 100% disposal to landfill; (iv) 50% recycling, 30% disposal to incineration plants and 20% disposal to landfill; and (v) 50% recycling, 20% disposal to incineration plants and 30% disposal to landfill. It was found that the end of life scenarios would affect ecotoxicity potential more and had less influence on other impact categories. Changes in ecotoxicity potential relevant impact categories were illustrated in Fig. 6(b). Similar trends were observed for marine and freshwater ecotoxicity potential assessed using CML2001, ILCD and Eco-Indicator99 but not exactly for terrestrial ecotoxicity potential. Marine and freshwater ecotoxicity potential could be reduced up to 79% if the scrap was fully recycled or disposed to landfill, but increased by 130–188% for the case of 100% disposal to incineration plants to the contrary. An approximately 25% reduction was observed when 50%, 20% and 30% of the scrap were respectively recycled, disposed to incineration plants and landfilled. With the same recycling rate but reversed ratios for incineration and landfill, the difference was imperceptible (as the rate for incineration was close to that in the base case). The trends shown by terrestrial ecotoxicity potential were dissimilar because in most scenarios, chromium and cast iron consumption during manufacturing phase had exerted a greater influence over the impact compared to metallic scrap disposal during end of life phase. The situation altered when the scrap was 100% disposed to landfill where a sharp increase in the potential was triggered. The findings proved that

- disposing scrap to incineration plants had the strongest impact on marine and freshwater ecotoxicity potential whilst recycling and disposing scrap to landfill had a moderate impact;
- reduction in some environmental burdens following a course of action (e.g. marine and freshwater ecotoxicity potential) would come along with an increase in other burdens (e.g. terrestrial ecotoxicity potential); and
- the end of life phase needed to be appropriately managed to avoid substantial burdens to the environment.

In reality, materials recovered from the end of life processes could have undergone a change in inherent properties and/or used for numerous purposes. For instance, aluminium recovered from the power system could be used in producing secondary ingots (i.e. materials for aluminium coils, semi-fabricated or finished aluminium components) or mixed with other elements such as copper, zinc, magnesium and silicon, to name a few, and turned into casting or wrought alloys. There was no definite answer on how exactly the recovered materials would be used and how many times each material could be recovered in reality. The wide range of materials involved in this study added complexities to the issue and hindered theoretical analysis. Due to time and resource constraints, the subsequent use of recovered materials was not considered in this study where a closed-loop end of life management plan was applied. The decision was made in line with the defined reason of the study i.e. to assess the environmental impact of a hybrid power system proposed for RoRo cargo ships. The estimated impact of the power system as presented in this study would vary provided an open-loop end of life management was considered. Without any in-depth investigation, to what degree such variation would be was uncertain.

4. Conclusions

It was argued that assessing the impact of a new-build hybrid power system from an LCA perspective was imperative. The assessment was required in line with the present direction towards sustainable shipping where existing LCA studies were relatively limited, if compared to the wide range of vessel types, technologies and system configurations. The need was intensified as previous studies on the environmental performance of marine transport mainly focussed on GHG emissions and climate change without exploring other impact on the natural environment. In accordance with ISO14040 and ISO14044, the LCA case study estimated the impact of a new-build hybrid power system designed for RoRo cargo ships which covered a range of impact categories. The hybrid system incorporated diesel gensets, PV and battery systems, cold-ironing, propellers and thrusters, motors and power electronics such as transformers, VFDs, AC-AC converters, inverters and rectifiers. In this case study, the life cycle of the hybrid system included energy and material acquisition, manufacture, operation and the end of life. In line with the defined goal and scope, the case study estimated resources and emissions involved throughout the life cycle, performed impact assessment, interpreted LCI and LCIA results and investigated significant processes via scenario analysis. It showed that materials and energy were consumed by up to 8 orders of magnitude. The most commonly consumed material was steel (i.e. 4.52×10^5 kg) which was required for manufacture. The largest energy source was MDO (i.e. 1.76×10^8 kg) which was burned during operation, followed by electricity (i.e. 6.58×10^6 MJ) required during dismantling. Also, emissions were released by up to 8 orders of magnitude, including 5.60×10^8 kg of CO_2, 2.43×10^5 kg of PM, 3.25×10^5 kg of HC, 1.13×10^7 kg of NO_X and 3.49×10^6 kg of SO_2. The LCIA results showed that the most burdensome impact categories assessed by CML2001, ILCD and Eco-Indicator99 were *Marine Aquatic Ecotoxicity Potential*, *Ecotoxicity for Aquatic Freshwater* and *Ecosystem Quality – Acidification/Nutrification*, which accounted for 5.92×10^{10} kg 1,4-DCB equivalent, 1.39×10^{10} CTUe and 6.81×10^7 PDF $* m^2 * a$ respectively. Among all processes, operating diesel gensets largely resulted in the impact categories that were relevant to PM/respiratory inorganic health issues, photochemical ozone creation, eutrophication, acidification and global warming. Disposing metallic scrap of diesel gensets, propellers and shafts, propulsion motors and thruster motors to incineration plants was significantly attributable to ecotoxicity potential. By comparing to a conventional system which had the same function and lifespan, it was found that the estimated LCIA results would vary by 1 order of magnitude (or less). The employment of the hybrid system could reduce the LCIA results estimated for 20 impact categories to the detriment of 6 impact categories. As reduction across all impact categories was impossible in practice, it was perceived that the decline in the majority of the impact categories had outweighed the increase in other impact categories. The environmental benefits that could be brought by the hybrid system in most impact categories were therefore verified. The work would be beneficial to both LCA and marine communities as it bridged existing knowledge gaps by assessing the implications of a hybrid power system and laid the groundwork for future study. The findings would be important in assisting regulators and ship owners in their decision making. The environmental burdens caused by the shipping industry in most impact categories could be reduced significantly provided hybrid power systems were widely employed onboard new-build vessels. The findings presented in this study should be revised in future if higher quality data were available, assumptions were dispelled and limitations were overcome. Also, future work should extend to present more case studies as well as comparative studies for different business routes, operational profiles, technologies, system designs and vessel types. In practice, the operation and the end of life of marine power systems should be planned, managed and monitored appropriately not only for energy efficiency but also for reduced implications on the natural environment.

Acknowledgements

Research findings presented in this article was the outcome of a FP7 project funded by European Commission, 'INOvative Energy MANagement System for Cargo SHIP' (INOMANS2HIP, grant agreement no: 266082) and a research funded by the Research Councils UK Energy Programme entitled 'Sustainable Thermal Energy Management Network' (SusTEM, EPSRC Reference: EP/K039377/1). Gratitude was extended to research consortium involved in the project, namely Imtech Marine Netherlands BV, Netherlands Organisation for Applied Scientific Research (TNO), Offshore Renewable Energy Catapult (NAREC), Wärtsilä Netherlands BV and the ship owner for their technical support and knowledge exchange. Data supporting this publication is openly available under an 'Open Data Commons Open Database License'. Additional metadata are available at: 10.17634/123881-1. Please contact Newcastle Research Data Service at rdm@ncl.ac.uk for access instructions.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2016.08.065.

References

[1] Review of maritime transport. In: Barki D, Rogers J, editors. New York and Geneva: United Nations Conference on Trade and Development (UNCTAD); 2015. p. 1–122.

[2] Attah EE, Bucknall R. An analysis of the energy efficiency of LNG ships powering options using the EEDI. Ocean Eng 2015;110:62–74.

[3] Schøyen H, Bråthen S. Measuring and improving operational energy efficiency in short sea container shipping. RTBM 2015;17:26–35.

[4] Cichowicz J, Theotokatos G, Vassalos D. Dynamic energy modelling for ship life-cycle performance assessment. Ocean Eng 2015;110, Part B:49–61.

[5] Johnson H, Styhre L. Increased energy efficiency in short sea shipping through decreased time in port. Transport Res A-Pol 2015;71:167–78.

[6] Bal Beşikçi E, Arslan O, Turan O, Ölçer AI. An artificial neural network based decision support system for energy efficient ship operations. Comput Oper Res 2016;66:393–401.

[7] Jafarzadeh S, Utne IB. A framework to bridge the energy efficiency gap in shipping. Energy 2014;69:603–12.

[8] Ovrum E, Bergh TF. Modelling lithium-ion battery hybrid ship crane operation. Appl Energy 2015;152:162–72.

[9] Pang KM, Karvounis N, Walther JH, Schramm J. Numerical investigation of soot formation and oxidation processes under large two-stroke marine diesel engine-like conditions using integrated CFD-chemical kinetics. Appl Energy 2016;169:874–87.

[10] Raptotasios SI, Sakellaridis NF, Papagiannakis RG, Hountalas DT. Application of a multi-zone combustion model to investigate the NOx reduction potential of two-stroke marine diesel engines using EGR. Appl Energy 2015;157:814–23.

[11] Hountalas DT, Papagiannakis RG, Zovanos G, Antonopoulos A. Comparative evaluation of various methodologies to account for the effect of load variation during cylinder pressure measurement of large scale two-stroke diesel engines. Appl Energy 2014;113:1027–42.

[12] Imperato M, Kaario O, Sarjovaara T, Larmi M. Split fuel injection and Miller cycle in a large-bore engine. Appl Energy 2016;162:289–97.

[13] Sigurdsson E, Ingvorsen KM, Jensen MV, Mayer S, Matlok S, Walther JH. Numerical analysis of the scavenge flow and convective heat transfer in large two-stroke marine diesel engines. Appl Energy 2014;123:37–46.

[14] Mueller L, Jakobi G, Czech H, Stengel B, Orasche J, Arteaga-Salas JM, et al. Characteristics and temporal evolution of particulate emissions from a ship diesel engine. Appl Energy 2015;155:204–17.

[15] Guan C, Theotokatos G, Zhou P, Chen H. Computational investigation of a large containership propulsion engine operation at slow steaming conditions. Appl Energy 2014;130:370–83.

[16] Zhao F, Yang W, Tan WW, Yu W, Yang J, Chou SK. Power management of vessel propulsion system for thrust efficiency and emissions mitigation. Appl Energy 2016;161:124–32.

[17] Baldi F, Theotokatos G, Andersson K. Development of a combined mean value-zero dimensional model and application for a large marine four-stroke Diesel engine simulation. Appl Energy 2015;154:402–15.

[18] Kowalski J. Concept of the multidimensional diagnostic tool based on exhaust gas composition for marine engines. Appl Energy 2015;150:1–8.

[19] Armstrong VN. Vessel optimisation for low carbon shipping. Ocean Eng 2013;73:195–207.

[20] Papanikolaou A. Holistic ship design optimization. Comput Aided Design 2010;42:1028–44.

[21] Fagerholt K, Psaraftis HN. On two speed optimisation problems for ships that sail in and out of emission control areas. Transport Res D – Tr E 2015;39:56–64.

[22] Yang M-H, Yeh R-H. Thermodynamic and economic performances optimization of an organic Rankine cycle system utilizing exhaust gas of a large marine diesel engine. Appl Energy 2015;149:1–12.

[23] Shu G, Liang Y, Wei H, Tian H, Zhao J, Liu L. A review of waste heat recovery on two-stroke IC engine aboard ships. Renew Sustain Energy Rev 2013;19:385–401.

[24] Cao T, Lee H, Hwang Y, Radermacher R, Chun H-H. Performance investigation of engine waste heat powered absorption cycle cooling system for shipboard applications. Appl Therm Eng 2015;90:820–30.

[25] Livanos GA, Theotokatos G, Pagonis D-N. Techno-economic investigation of alternative propulsion plants for ferries and RoRo ships. Energy Convers Manag 2014;79:640–51.

[26] Baldi F, Larsen U, Gabrielii C. Comparison of different procedures for the optimisation of a combined diesel engine and organic Rankine cycle system based on ship operational profile. Ocean Eng 2015;110, Part B:85–93.

[27] Welaya Y, El Gohary MM, Ammar NR. A comparison between fuel cells and other alternatives for marine electric power generation. Int J Nav Arch Ocean 2011;3:141–9.

[28] Tse LKC, Wilkins S, McGlashan N, Urban B, Martinez-Botas R. Solid oxide fuel cell/gas turbine trigeneration system for marine applications. J Power Sources 2011;196:3149–62.

[29] Lan H, Wen S, Hong Y-Y, Yu DC, Zhang L. Optimal sizing of hybrid PV/diesel/battery in ship power system. Appl Energy 2015;158:26–34.

[30] Traut M, Gilbert P, Walsh C, Bows A, Filippone A, Stansby P, et al. Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. Appl Energy 2014;113:362–72.

[31] Li Q, Nihei Y, Nakashima T, Ikeda Y. A study on the performance of cascade hard sails and sail-equipped vessels. Ocean Eng 2015;98:23–31.
[32] Coppola T, Fantauzzi M, Lauria D, Pisani C, Quaranta F. A sustainable electrical interface to mitigate emissions due to power supply in ports. Renew Sustain Energy Rev 2016;54:816–23.
[33] Sciberras EA, Zahawi B, Atkinson DJ. Electrical characteristics of cold ironing energy supply for berthed ships. Transport Res D – Tr E 2015;39:31–43.
[34] Ballini F, Bozzo R. Air pollution from ships in ports: the socio-economic benefit of cold-ironing technology. RTBM 2015;17:92–8.
[35] Roskilly AP, Palacin R, Yan J. Novel technologies and strategies for clean transport systems. Appl Energy 2015;157:563–6.
[36] Third IMO GHG study. International Maritime Organization (IMO). Available from: <http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Greenhouse-Gas-Studies-2014.aspx>; 2014 [Cited 2016, 4 February].
[37] Lister J, Poulsen RT, Ponte S. Orchestrating transnational environmental governance in maritime shipping. Global Environ Chang 2015;34:185–95.
[38] Walsh C, Bows A. Size matters: exploring the importance of vessel characteristics to inform estimates of shipping emissions. Appl Energy 2012;98:128–37.
[39] Heitmann N, Peterson S. The potential contribution of the shipping sector to an efficient reduction of global carbon dioxide emissions. Environ Sci Policy 2014;42:56–66.
[40] Lindstad H, Sandaas I, Steen S. Assessment of profit, cost, and emissions for slender bulk vessel designs. Transport Res D – Tr E 2014;29:32–9.
[41] Jiven K, Sjobris A, Nilsson M, Ellis J, Tragardh P, Nordstrom M. LCA-ship, design tool for energy efficient ships – a life cycle analysis program for ships. Sweden: MariTerm AB, TEM and SSPA Sweden AB; 2004.
[42] Kameyama M, Hiraoka K, Sakurai A, Naruse T, Tauchi H. Development of LCA software for ships and LCI analysis based on actual shipbuilding and operation. In: Proc 6th Int Conf on Ecobalance.
[43] Kameyama M, Hiraoka K, Tauchi H. Study on life cycle impact assessment for ships. Japan: NMRI; 2007.
[44] Tincelin T, Mermier L, Pierson Y, Pelerin E, Jouanne G. A life cycle approach to shipbuilding and ship operation. In: Ship design and operation for environmental sustainability. London: The Royal Institution of Naval Architects; 2007.
[45] Prinĉaud M, Cornier A, Froëlich D. Developing a tool for environmental impact assessment and eco-design for ships. Proc Inst Mech Eng, Part M: J Eng Marit Environ 2010;224:207–24.
[46] Basurko OC, Mesbahi E. Methodology for the sustainability assessment of marine technologies. J Clean Prod 2014;68:155–64.
[47] Fet AM, Sørgård E. Life cycle evaluation of ship transportation – development of methodology and testing. Aalesund College (HiA) in Cooperation with Det Norske Veritas (DNV)(HiA 10/B101/R-98/008/00); 1998. p. 32.
[48] Fet AM. Environmental reporting in marine transport based on LCA. Proc IMarEST J Marine Design Oper 2002:1476–556.
[49] Schmidt JH, Watson J. Eco Island Ferry: comparative LCA of island ferry with carbon fibre composite based and steel based structures. 2.-0 LCA consultants; 2014.
[50] Alkaner S, Zhou P. A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application. J Power Sources 2006;158:188–99.
[51] Strazza C, Del Borghi A, Costamagna P, Traverso A, Santin M. Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships. Appl Energy 2010;87:1670–8.
[52] Strand KH, Aarskog KJ. Life cycle assessment of fuel cells onboard ships. Trondheim: Norwegian University of Science and Technology; 2010.
[53] Ling-Chin J, Heidrich O, Roskilly AP. Life cycle assessment (LCA) – from analysing methodology development to introducing an LCA framework for marine photovoltaic (PV) systems. Renew Sustain Energy Rev 2016;59:352–78.
[54] Ling-Chin J, Roskilly AP. Investigating a conventional and retrofit power plant on-board a Roll-on/Roll-off cargo ship from a sustainability perspective – a life cycle assessment case study. Energy Convers Manag 2016;117:305–18.
[55] Ma H, Steernberg K, Riera-Palou X, Tait N. Well-to-wake energy and greenhouse gas analysis of SOx abatement options for the marine industry. Transport Res D – Tr E 2012;17:301–8.
[56] Bengtsson S, Andersson K, Fridell E. A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels. P I Mech Eng M – J Eng 2011;225:97–110.
[57] Bengtsson S, Fridell E, Andersson K. Environmental assessment of two pathways towards the use of biofuels in shipping. Energy Pol 2012;44:451–63.
[58] Zuin S, Belac E, Marzi B. Life cycle assessment of ship-generated waste management of Luka Koper. Waste Manage 2009;29:3036–46.
[59] Chatzinikolaou SD, Ventikos NP. Holistic framework for studying ship air emissions in a life cycle perspective. Ocean Eng 2015;110, Part B:113–22.
[60] EC funding gives green light to ambitious IMO energy-efficiency project. International Maritime Organisation. Available from: <http://www.imo.org/en/MediaCentre/PressBriefings/Pages/01-2016-MTCC-.aspx>; 2016 [Cited 2016, 26 May].
[61] Low Emission Accelerator Partnership (LEAP). United States Maritime Administration. Available from: <http://www.grants.gov/search-grants.html?agencies%3DDOT|Department%20of%20Transportation>; 2015 [Cited 2016, 26 May].
[62] Funding agreed for Global Maritime Energy Efficiency Partnerships Project (GloMEEP). International Maritime Organisation. Available from: <http://www.imo.org/en/MediaCentre/PressBriefings/Pages/35-glomeep-signing.aspx>; 2015 [Cited 2016, 26 May].
[63] Henriksson T, Murphy M, Zee E, Riksheim R, Steen S, Adnanes AK. Electric propulsion – state-of-the-art and trends in electric power generation, distribution, and propulsion, and their associated control systems. In: Kare AA, Hansen J-F, editors. 8th ICMES/SNAME New York Metropolitan Section Symposium. New York: The Society of naval Architects and Marine Engineers; 2000.
[64] Kanerva S, Hansen J-F. State of the art in electric propulsion – viewpoint on redundancy. In: Electric ship technologies symposium, 2009 ESTS 2009 IEEE. IEEE; 2009. p. 499–504.
[65] McCoy TJ. Trends in ship electric propulsion. In: Power engineering society summer meeting, 2002 IEEE. IEEE; 2002. p. 343–6.
[66] Buja G, Rin AD, Menis R, Sulligoi G. Dependable design assessment of integrated power systems for all electric ships. Electrical systems for aircraft, railway and ship propulsion (ESARS), 2010. IEEE; 2010. p. 1–8.
[67] Prousalidis JM, Tsekouras GJ, Kanellos F. New challenges emerged from the development of more efficient electric energy generation units. Electric ship technologies symposium (ESTS), 2011 IEEE. IEEE; 2011. p. 374–81.
[68] Kanellos FD, Prousalidis JM, Tsekouras GJ. Control system for fuel consumption minimisation – gas emission limitation of full electric propulsion ship power systems. P I Mech Eng M – J Eng 2014;228:17–28.
[69] Skjong E, Rodskar E, Molinas M, Johansen T, Cunningham J. The marine vessel's electrical power system: from its birth to present day. Proc IEEE 2015;103:2410–24.
[70] Dale S, Hebner R, Sulligoi G. Electric ship technologies. Proc IEEE 2015;103:2225–8.
[71] Environmental management – life cycle impact assessment – principles and framework. British Standard; 2006.
[72] Environmental management – life cycle impact assessment – requirements and guidelines. International Organisation for Standardisation (ISO); 2006.
[73] Bare JC, Gloria TP. Critical analysis of the mathematical relationships and comprehensiveness of life cycle impact assessment approaches. Environ Sci Technol 2006;40:1104–13.
[74] Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, et al. Life cycle assessment: an operational guide to the ISO standards–Part 3 Scientific Background. The Netherlands: Centre of Environmental Science (CML); 2001.
[75] ILCD Handbook: Framework and requirements for life cycle impact assessment models and indicators. Luxembourg; 2010.
[76] Goedkoop M, Spriensma R. The eco-indicator99: a damage oriented method for life cycle impact assessment: methodology report. Available from: <http://www.teclim.ufba.br/jsf/indicadores/holan%20ecoindicator%2099.pdf>; 2001 [Cited 2016, 10 July].
[77] Rampen P, Meijer C, Gunput S, Pelaez-Carus M, Bradley T, Van Vugt H, et al. Deliverable D3.1 energy characteristics modelling. WP3 Interfaces and network design. Available from: <http://www.narecde.co.uk/wp-content/uploads/2014/11/D3-1_INOMANS%C2%B2HIP_M30_v2.pdf>; 2013. p. 1–110 [Cited 2016, 10 July].
[78] Yellishetty M, Mudd GM, Ranjith PG, Tharumarajah A. Environmental life-cycle comparisons of steel production and recycling: sustainability issues, problems and prospects. Environ Sci Policy 2011;14:650–63.
[79] Norgate TE. Metal recycling: an assessment using life cycle energy consumption as a sustainability indicator. Minerals, Editor; 2004.
[80] Kaplan RS, Ness H. Recycling of metals. Conserv Recycling 1987;10:1–13.
[81] Moats M, Ramachandran V, Robinson T, Davenport WG. Recycling of nickel, cobalt and platinum-group metals. Extractive metallurgy of nickel, cobalt and platinum group metals. Elsevier; 2011.
[82] Johnson J, Reck BK, Wang T, Graedel TE. The energy benefit of stainless steel recycling. Energy Pol 2008;36:181–92.
[83] Gaustad G, Olivetti E, Kirchain R. Improving aluminum recycling: a survey of sorting and impurity removal technologies. Resour Conserv Recy 2012;58:79–87.
[84] Paraskevas D, Kellens K, Dewulf W, Duflou JR. Environmental modelling of aluminium recycling: a life cycle assessment tool for sustainable metal management. J Clean Prod 2015;105:357–70.
[85] Green JAS. Aluminum recycling and processing for energy conservation and sustainability. ASM International; 2007.
[86] Craighill AL, Powell JC. Lifecycle assessment and economic evaluation of recycling: a case study. Resour Conserv Recy 1996;17:75–96.
[87] Trozzi C, Kuenen J, Nielsen O-K, Rentz O, Oertel D, Woodfield M, et al. EMEP/EEA air pollutant emission inventory guidebook 2013: technical guidance to prepare national emission inventories. Luxembourg; 2013.
[88] Muchova L, Eder P, Villanueva A. End-of-waste criteria for copper and copper alloy scrap. Spain: European Commission; 2011.
[89] Gordon RB, Graedel TE, Bertram M, Fuse K, Lifset R, Rechberger H, et al. The characterization of technological zinc cycles. Resour Conserv Recy 2003;39:107–35.
[90] Genaidy AM, Sequeira R, Tolaymat T, Kohler J, Rinder M. Evidence-based integrated environmental solutions for secondary lead smelters: pollution prevention and waste minimization technologies and practices. Sci Total Environ 2009;407:3239–68.

[91] Reck BK, Müller DB, Rostkowski K, Graedel TE. Anthropogenic nickel cycle: insights into use, trade, and recycling. Environ Sci Technol 2008;42:3394–400.
[92] Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R. ReCiPe 2008 – a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. The Netherlands; 2009. p. 126.
[93] Chan YT, Tan RBH, Khoo HH. Characterisation framework development for the SIMPASS (Singapore impact assessment) methodology. Int J Life Cycle Assess 2012;17:89–95.